Latest ν oscillation results from T2K

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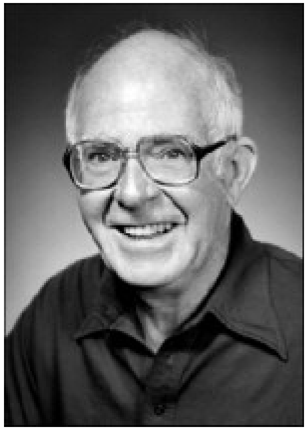
Outline

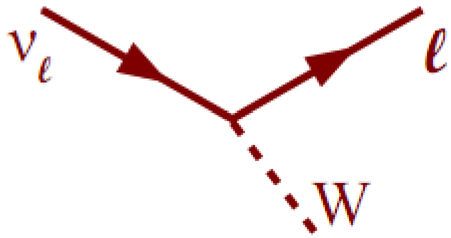
- Neutrino oscillation: status and goals
- T2K experiment: design concept, components
- Far detector event selection
- Oscillation analysis result:
  - $\nu_\mu \to \nu_e$ appearance
  - $\nu_\mu \to \nu_\mu$ disappearance
- Conclusion (and future prospects)

Neutrino mixing



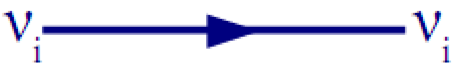
- Neutrino oscillation implies that neutrinos have mass and the mass eigenstates and the weak eigenstates are not identical
- One set is the linear combination of the other (3-ν framework):

Weak states



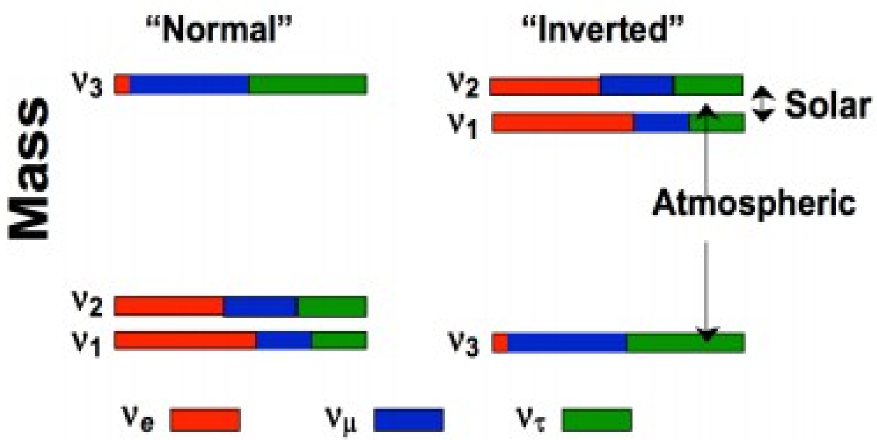
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass states



$E^2 = p^2 + m^2$

U: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino-mixing matrix



There are two independent mass differences: $\Delta m_{ij}^2 = m_i^2 - m_j^2$

that drive ν oscillations: Δm_{21}^2 , Δm_{32}^2

$|\Delta m_{32}^2|$:only its absolute value is known

$\rightarrow$ ambiguous mass ordering!

Neutrino mixing status

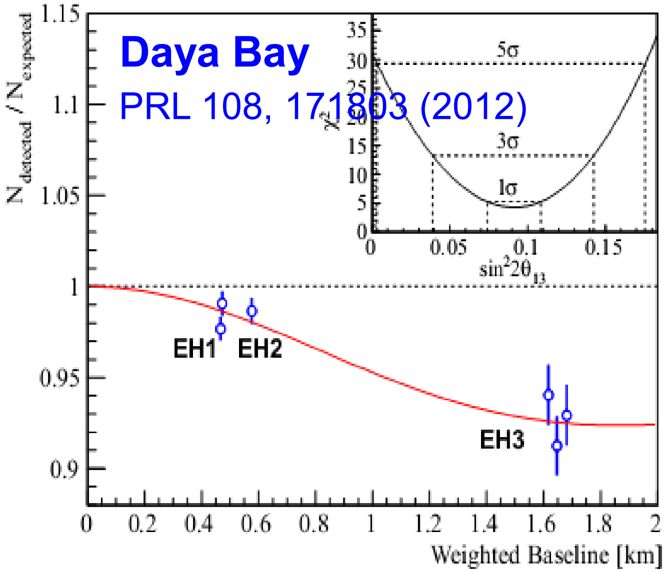
- 3-flavor mixing: PMNS (unitary) matrix can be parametrized by three mixing angles (θ_{ij}) and one complex (CP violating) phase (δ):

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\boxed{\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}}\times\underbrace{\begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta}\\0&1&0\\-\sin\theta_{13}e^{i\delta}&0&\cos\theta_{13}\end{pmatrix}}\times\boxed{\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}}\times\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric & accelerator:
$\theta_{23} \approx 45^\circ \pm 6^\circ$
$(\Delta m_{23})^2 = 2.3\text{x}10\text{-}3\ \text{eV}^2$

Interference:
$\Theta_{13} \approx 9.1^\circ \pm 0.6^\circ$

Solar & reactor:
$\Theta_{12\approx}\ 34^\circ \pm 1^\circ$
$(\Delta m_{12})^2 = 7.5\text{x}10\text{-}5\ \text{eV}^2$



- first hint of non-zero θ_{13} from T2K (2011)
- conclusive measurement by reactor experiments (Daya Bay, Double Chooz, RENO) in 2012

Goal of next generation experiments:
- CPV phase: δ_{CP}
- mass hierarchy ($\Delta m^2_{23} > 0?$)
- is θ_{23} maximal (45°)?

Neutrino oscillation

- Neutrino mixing leads to a reach neutrino oscillation phenomenon
- At accelerator-based oscillation experiments (ν_μ beam) one can study

ν_μ disappearance:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 1.27 \frac{\Delta m^2_{32} L}{E_\nu}$$

sensitive to parameters θ_{23} and Δm^2_{32}

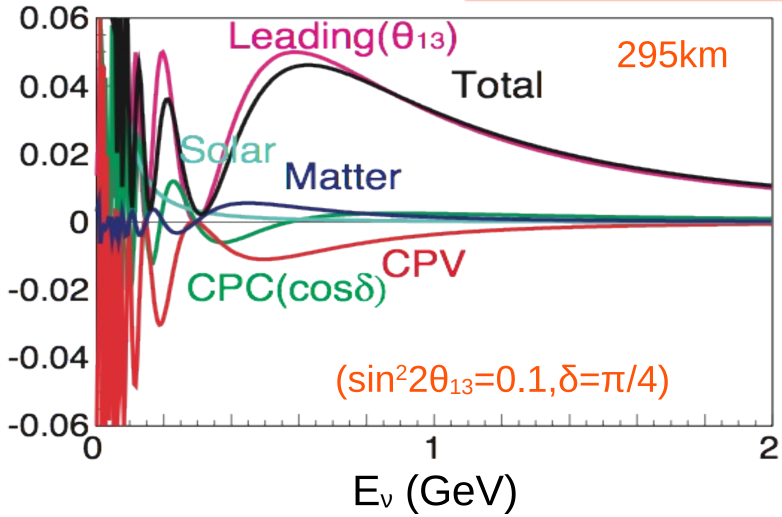
ν_e appearance:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \text{CPV term} + \text{subleading terms}$$

sensitive to parameter θ_{13}

sensitive to parameter δ

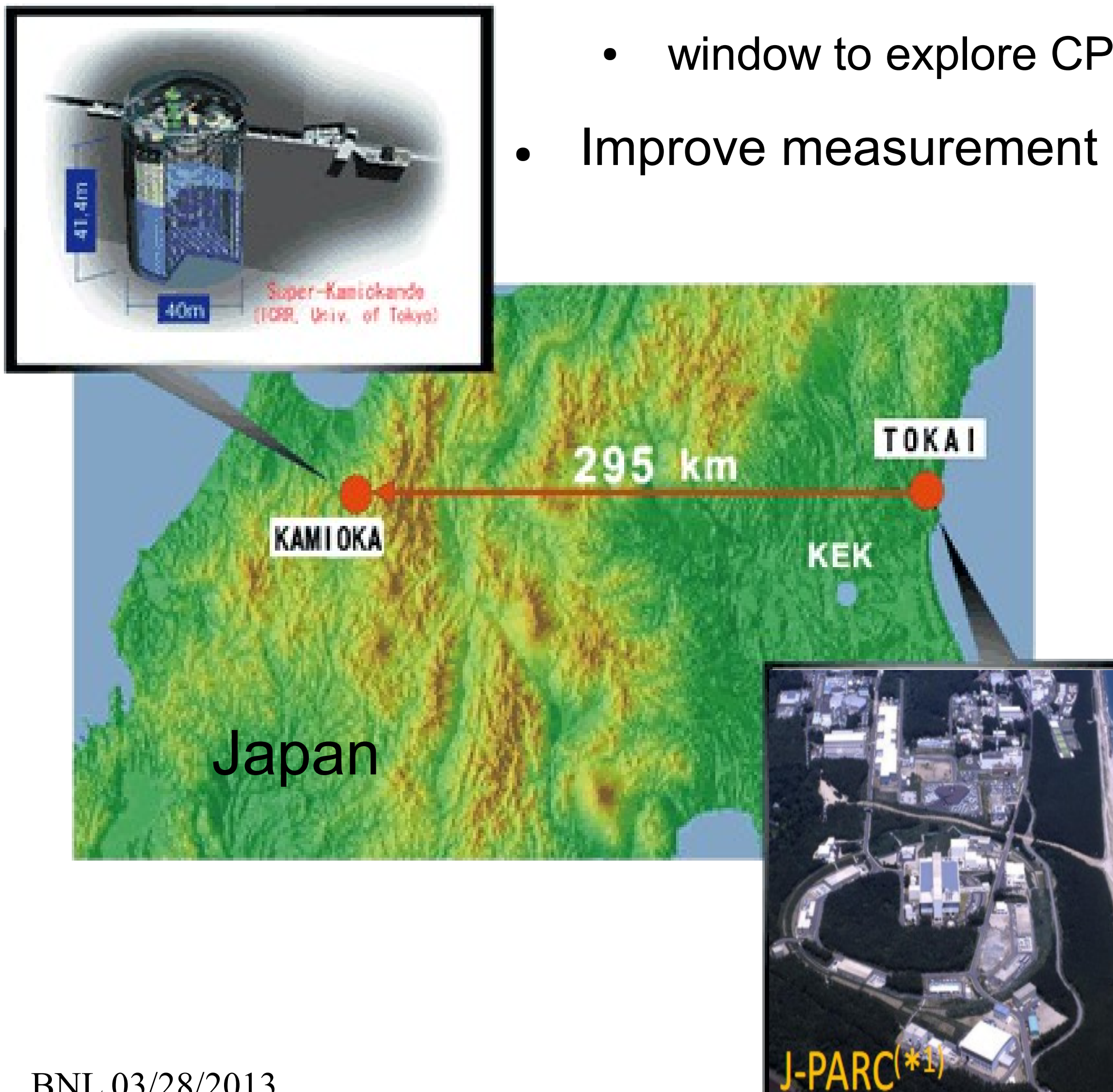
containing matter effect terms - change sign for $\bar{\nu}_\mu$ - mass hierarchy



The Tokai-to-Kamioka experiment

Main objectives:

- Discover (and measure) $\nu_\mu \rightarrow \nu_e$ appearance (θ_{13})
  - window to explore CPV in leptonic sector (δ)
- Improve measurement of Δm^2_{23} and θ_{23} in ν_μ disappearance

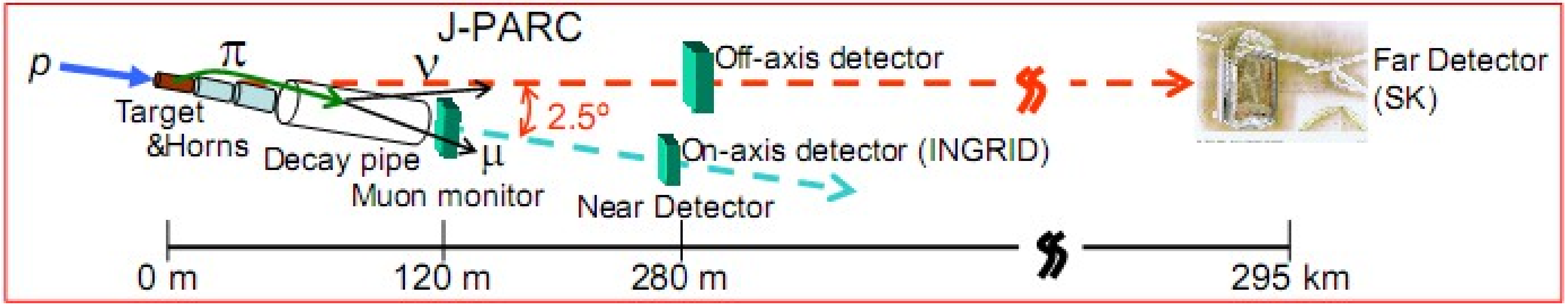


Requirements:

- Very intense ν beam
- Massive far detector (Super-K)
- Long baseline (295 km)
- Near detector (ν flux and composition near source)
- Off-axis design
  - enhance sensitivity at oscillation maximum
  - reduce intrinsic background

Off-axis beam concept

- T2K is the first long-baseline ν experiment using an off-axis beam



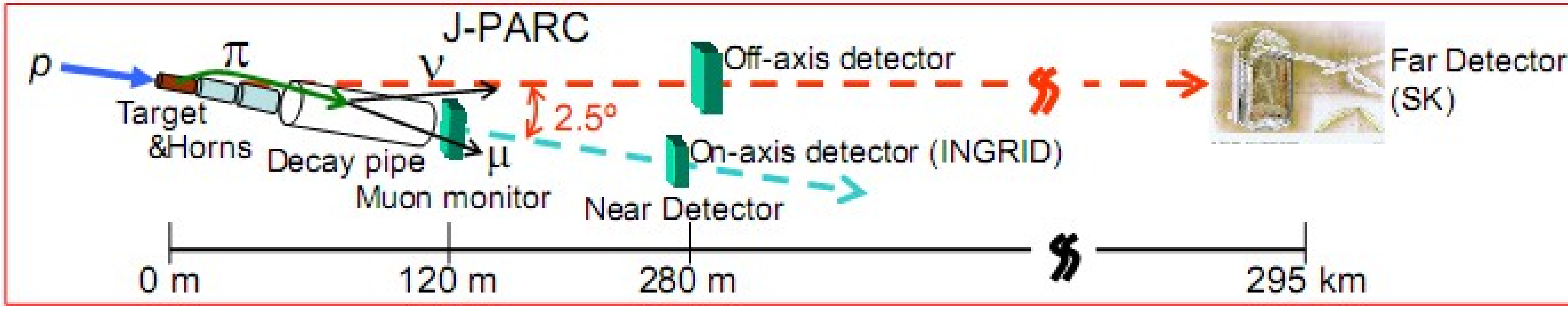
- The concept has been proposed first by a BNL design report

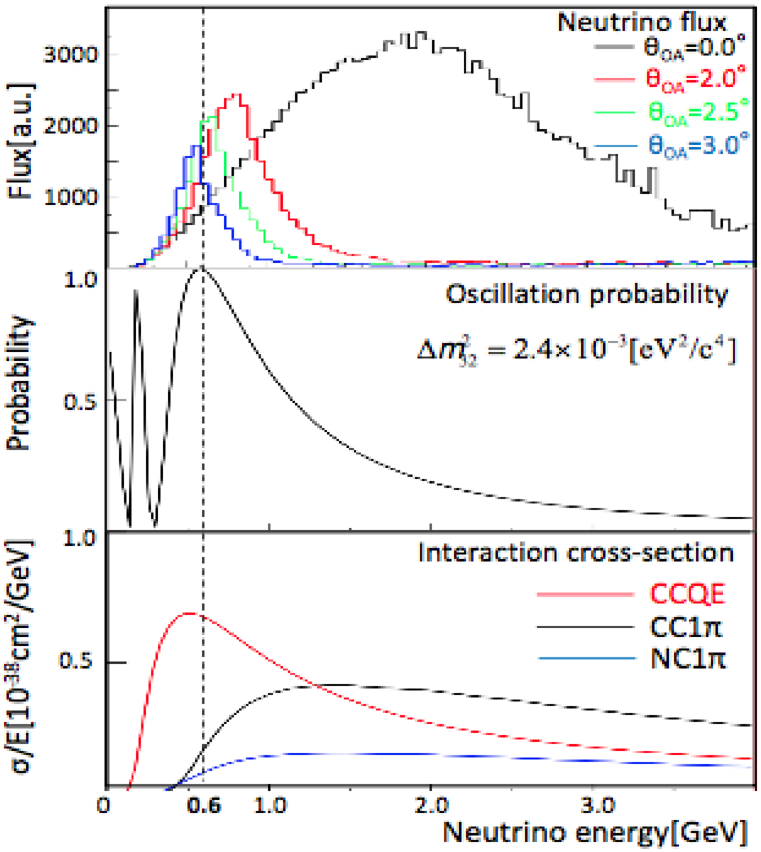
Long-baseline neutrino oscillation experiment at the AGS, D. Beavis, A. Carroll, I. Chiang, M. Diwan, *et al.* (E889 Collaboration), Physics Design Report, BNL 52459 (1995)

> Abstract: … A key aspect of the experimental design involves <u>placing the detectors 1.5 degrees off the center line of the neutrino beam</u>, which has the important advantage that the central value of the neutrino energy ({approx} 1 GeV) and the beam spectral shape are, to a good approximation, the same in all four detectors. ...

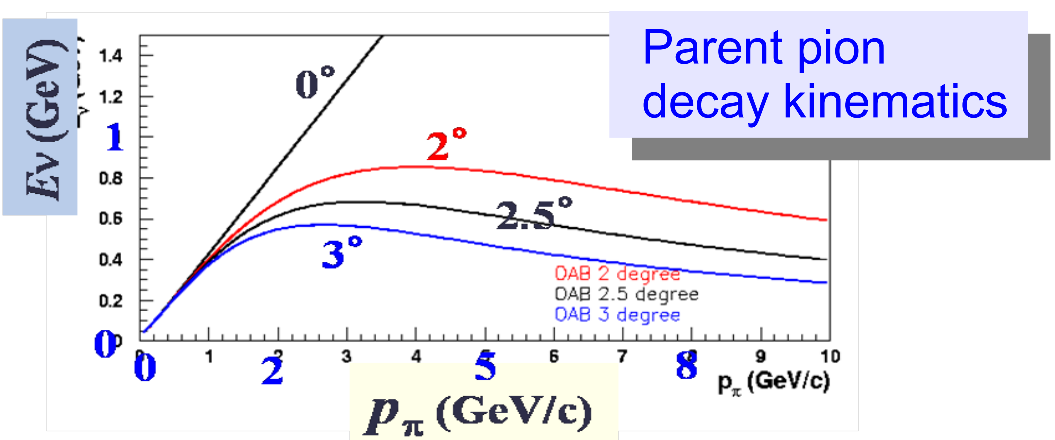
T2K off-axis beam

- The ν beam is aimed 2.5° off the direction of Super-Kamikande:

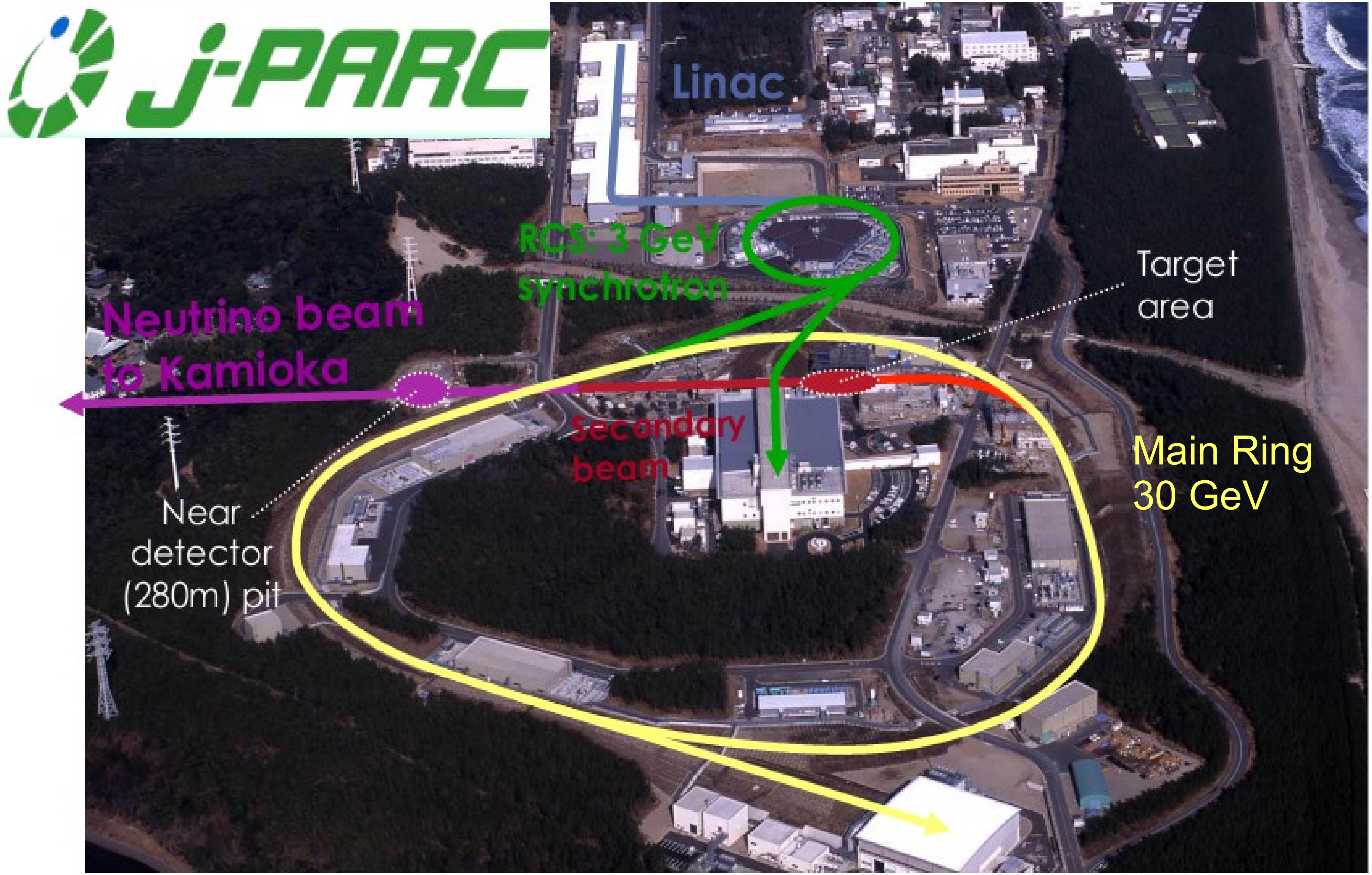




- Narrow-band beam with peak energy (~600 MeV) tuned to first oscillation maximum: more sensitive to oscillation
- Reduced background due to non-QE interactions and NC feed down from high energy ν_μ tail



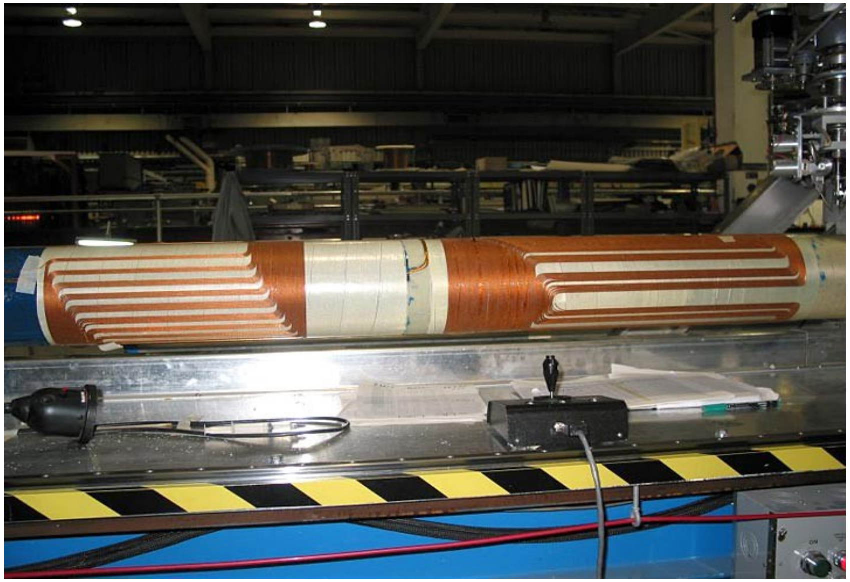
Accelerator complex

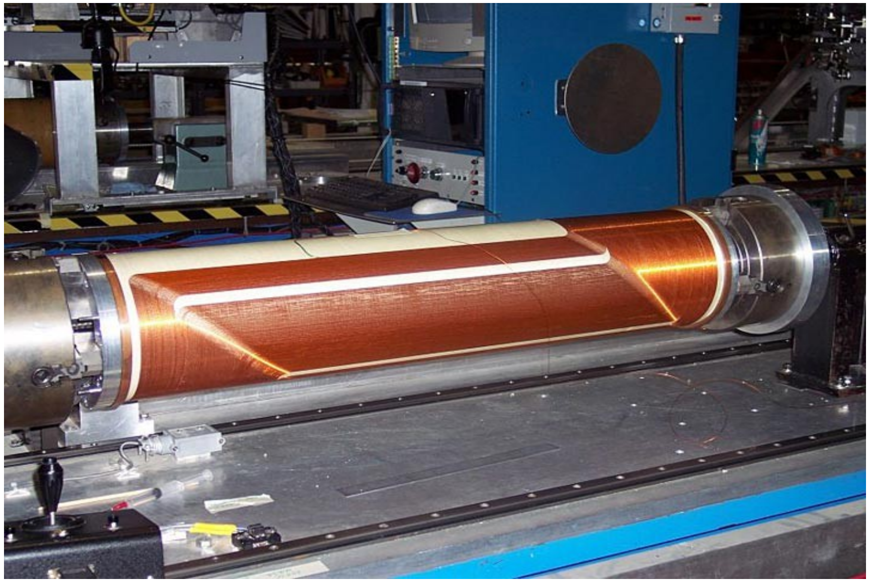


Made in BNL

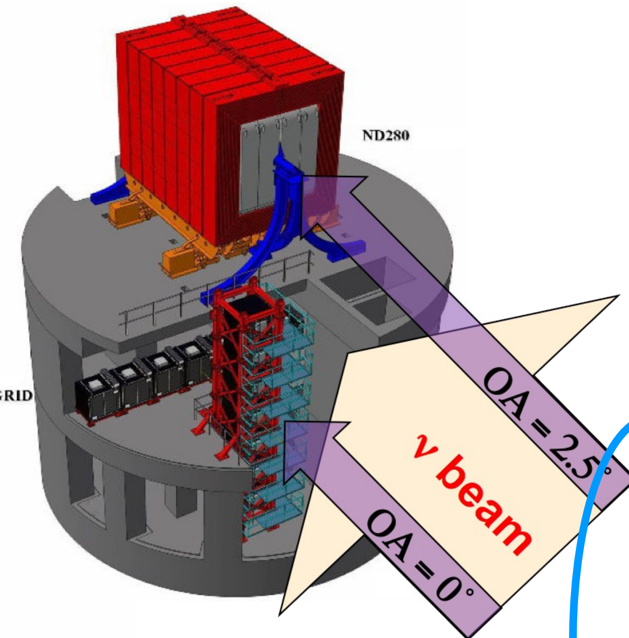
BNL Superconducting Magnet Division (Peter Wanderer, head) contributed to T2K proton beam line:

- combined function (bend+focus) principal magnets: some of the design concepts were adopted from the RHIC magnets
- combined function corrector magnets: constructed at BNL





Near detector complex

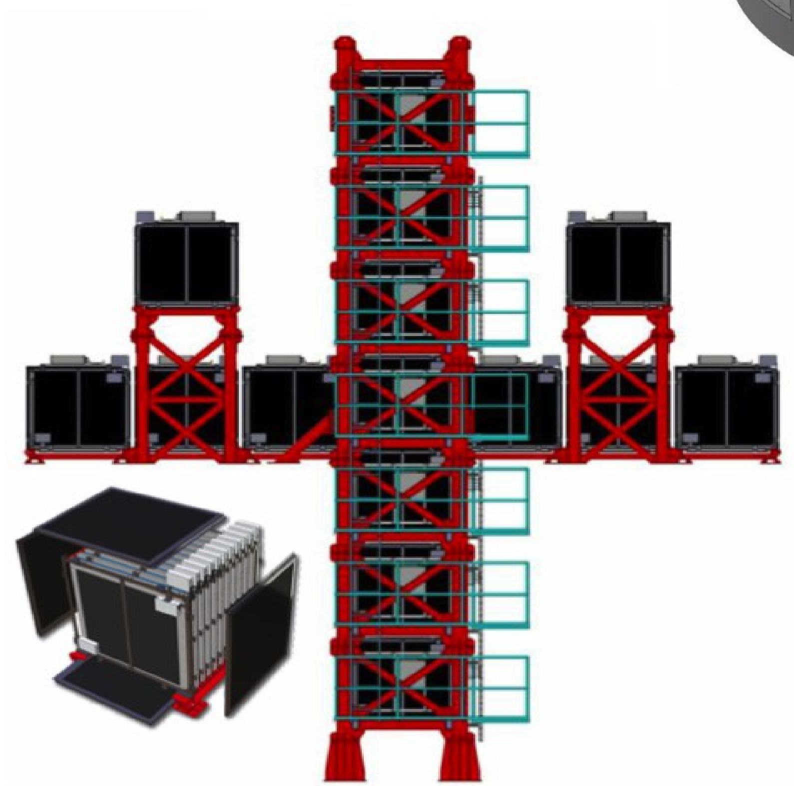


On-axis: INGRID

ν beam direction and profile

7+7+2 modules
- scintillator/iron sandwich
- 10x10 m^2

+1 proton (no iron) module



Off-axis: ND280

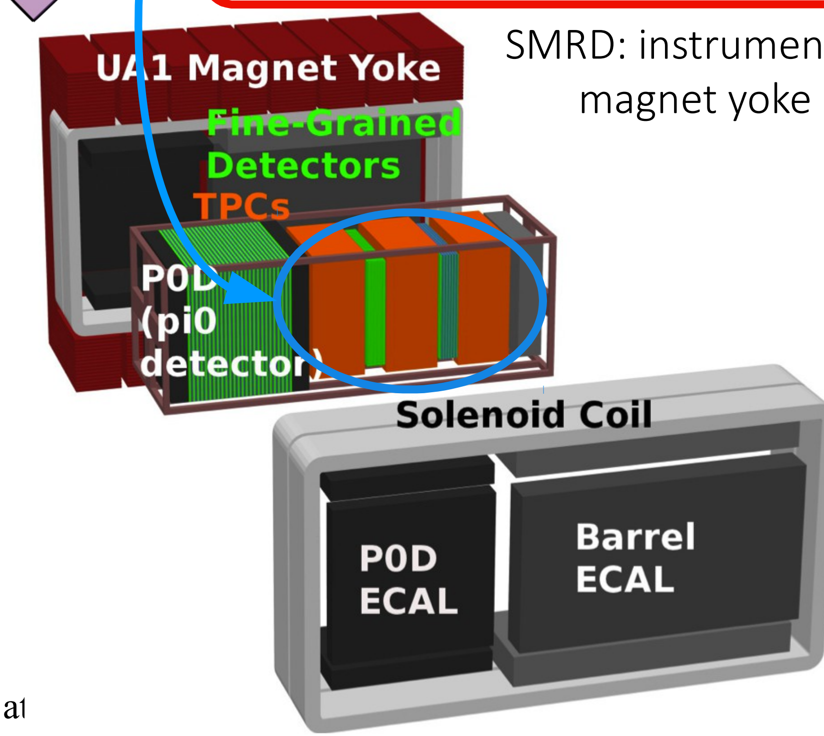
ν flux norm./spectrum and cross sections

inside UA1 magnet (0.2 T):

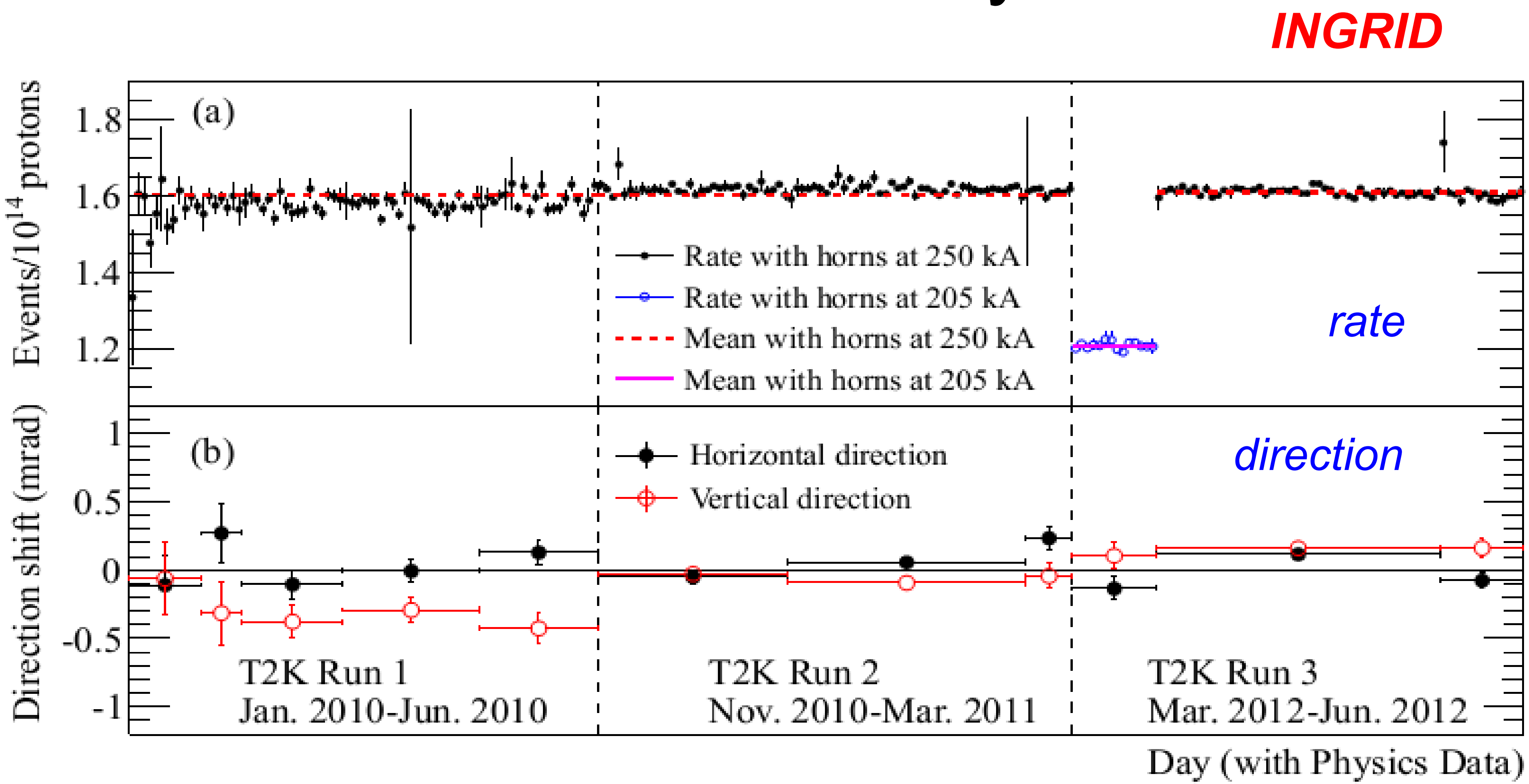
2 fine-grained detectors (FGD)
water/carbon target
3 gas TPCs

π0 detector (P0D)
electromagnetic calorimeter (ECal)

SMRD: instrumented magnet yoke

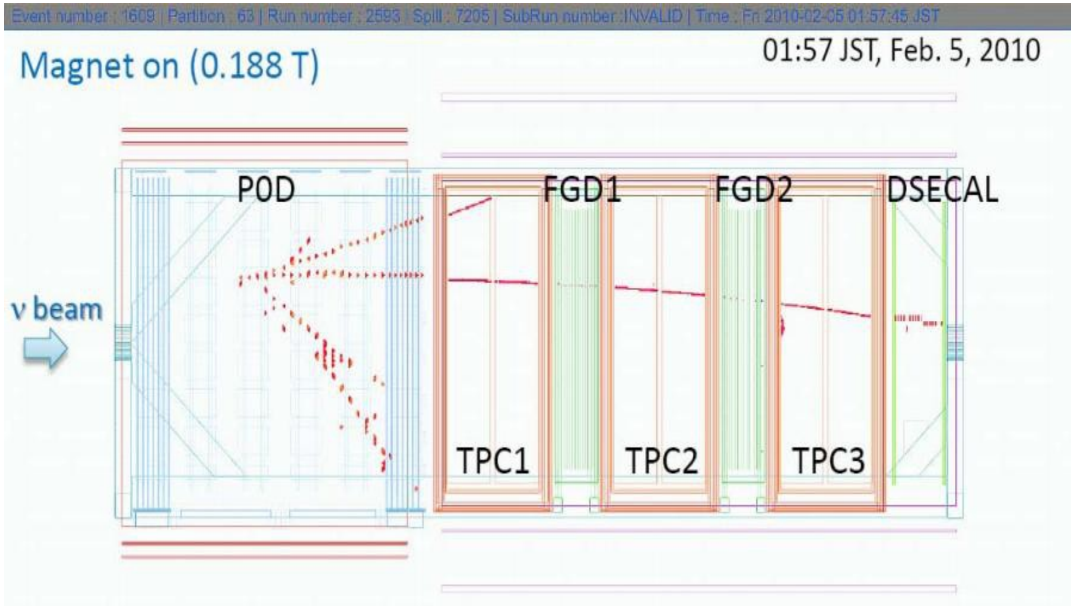


Beam stability

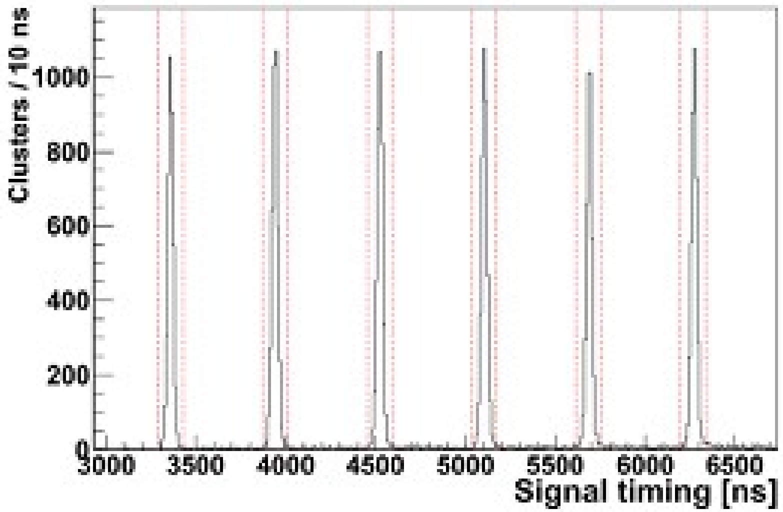


- Beam direction is stable well within 1 mrad requirement (<2% shift in peak beam energy!)

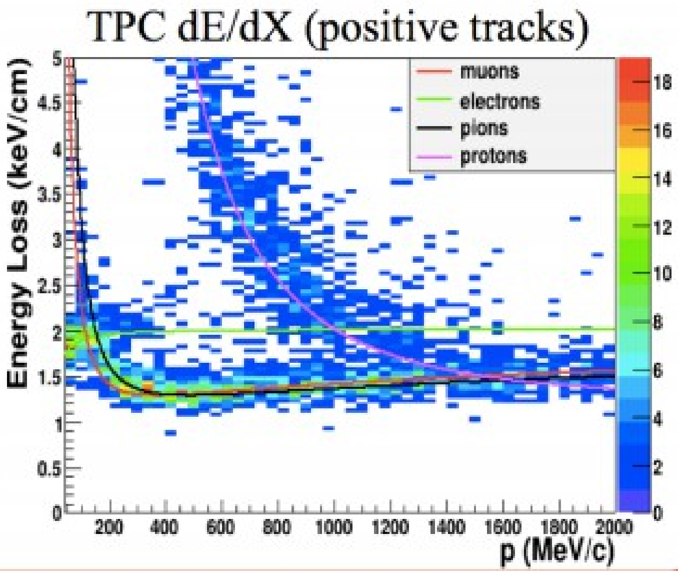
ND280 performance

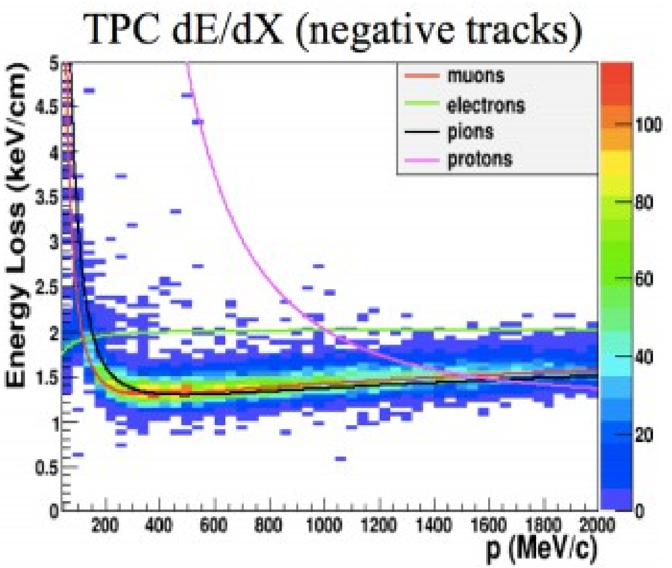


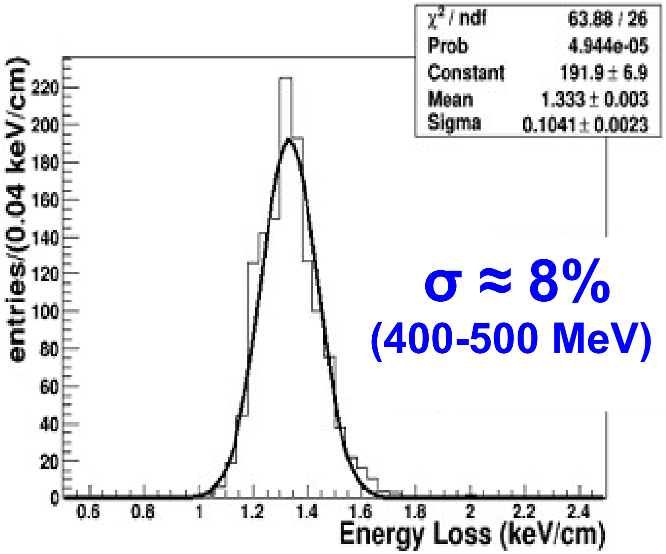
FGD cluster timing (w/ 6 beam bunches)



Excellent spatial, momentum, and timing resolution, and PID capabilities!



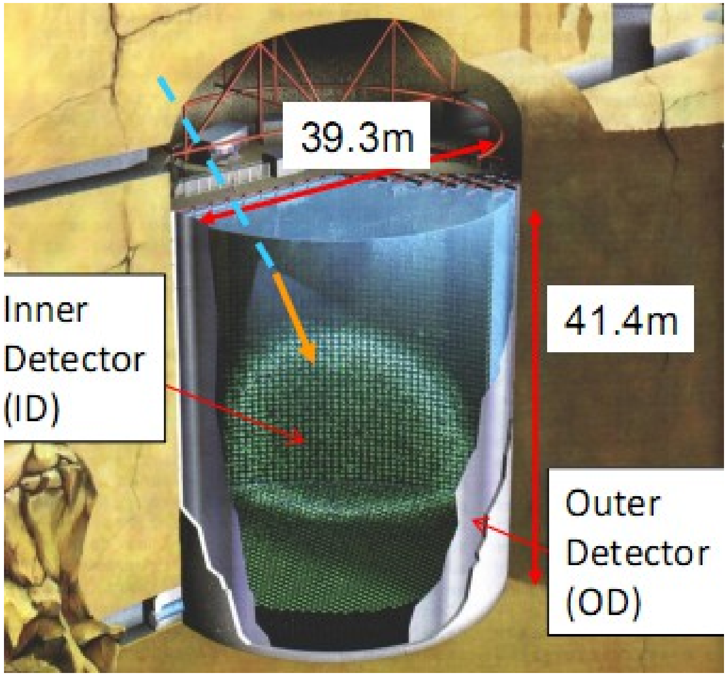


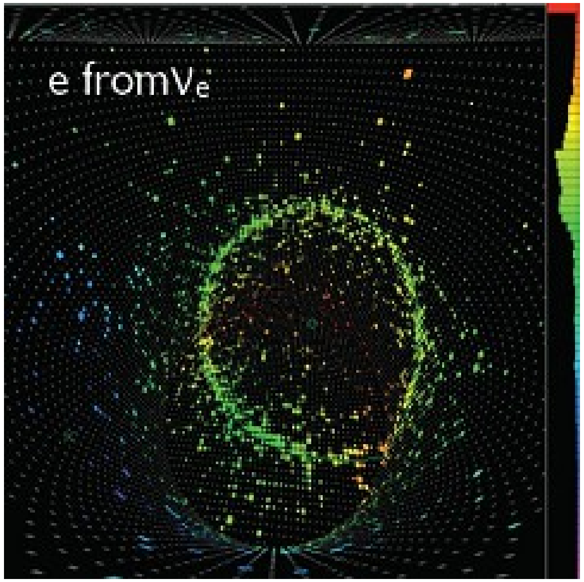


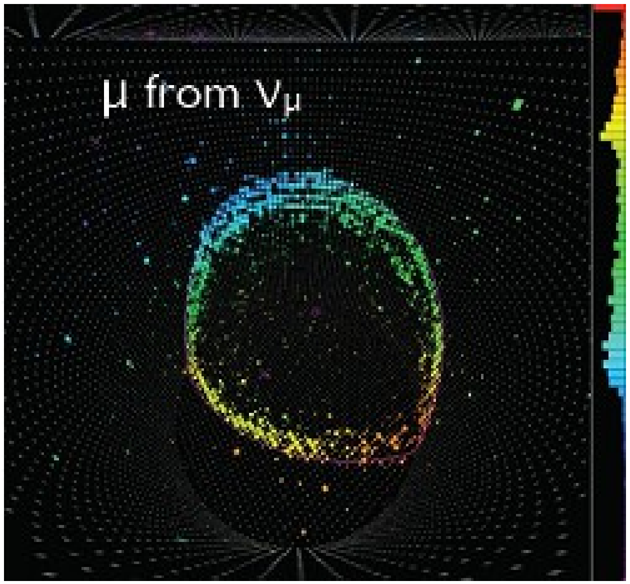
σ ≈ 8%
(400-500 MeV)

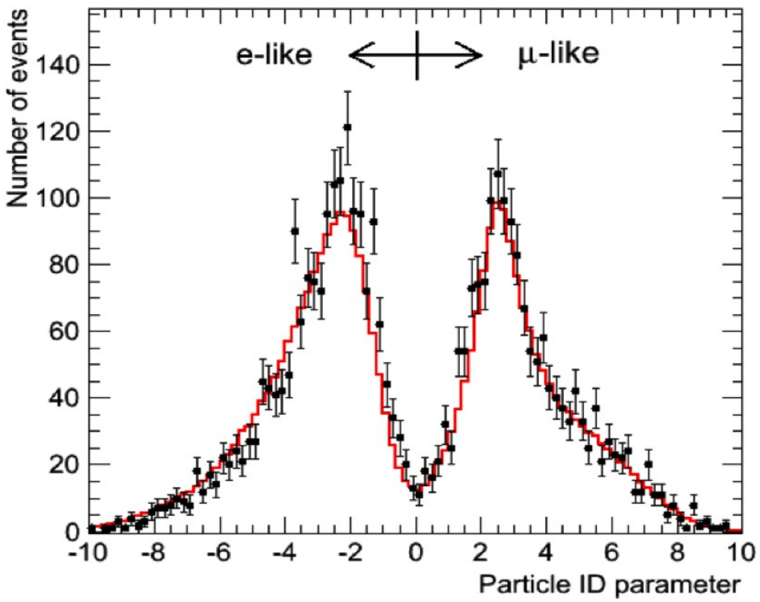
Far detector: Super Kamiokande IV

- Water Cherenkov det.: 50 kton (22.5 kton fiducial)
- ID: 11k 20" PMT (40% photo coverage); OD: 2k 8" veto PMT (optically isolated from ID)
- New readout electronics and DAQ: no dead time (improved decay-electron tagging)
- GPS based event timing
- Very efficient e/μ separation based on light pattern (~99% at 0.6 GeV)

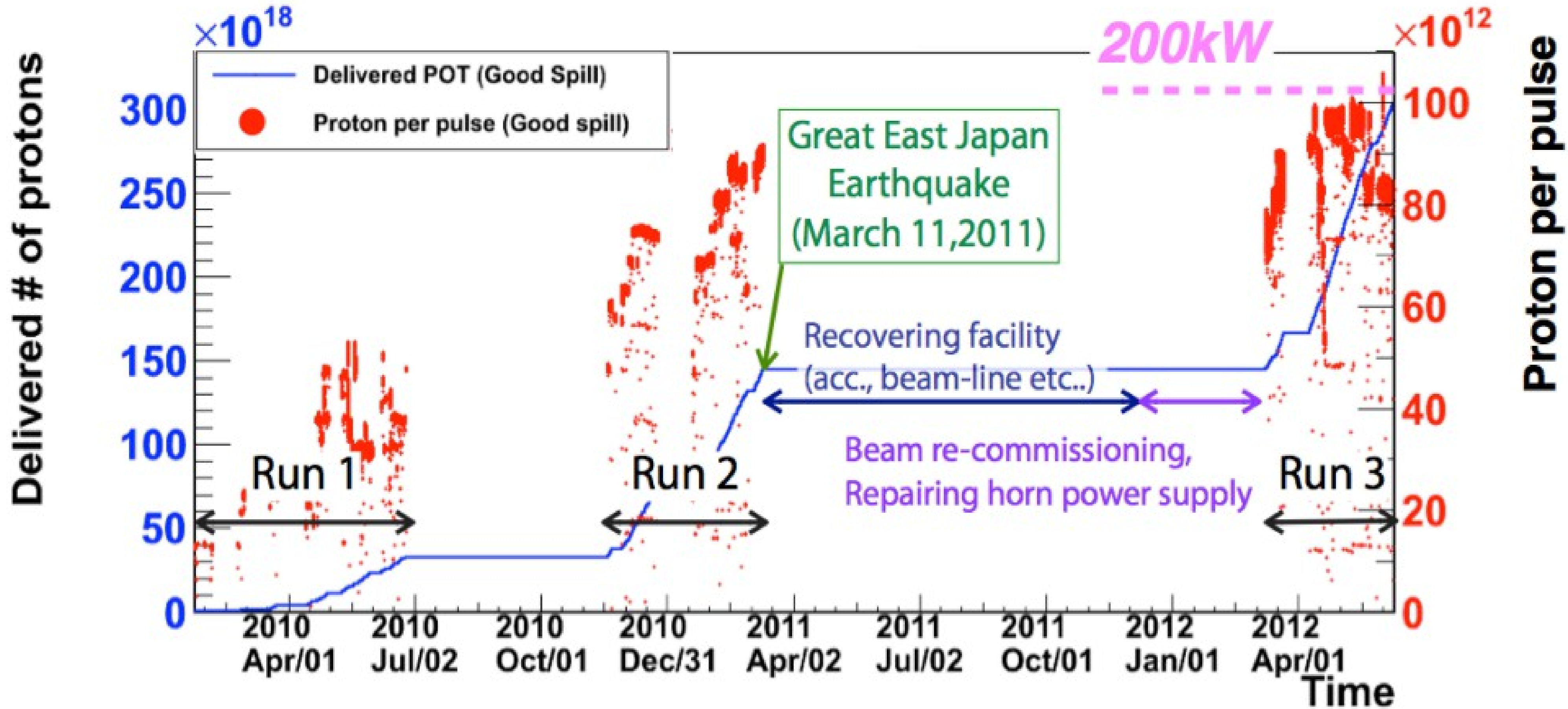








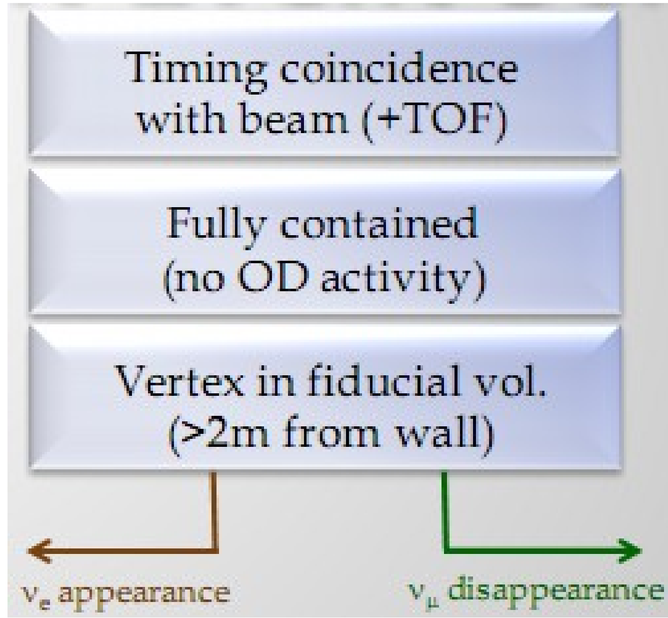
T2K data until June 2012



- Latest results based on Run 1-3 data
  - integrated POT: 3.01×10^{20} (4% of approved total POT)
  - first publication in 2011 used Run 1+2 (1.43×10^{20} POT)
- Stable running at up to 200 kW ($\geq 1 \times 10^{14}$ POT/spill)

SK event selection

Pre-selection:



ν_e selection

- $E_{vis} > 100$ MeV
- 1 e-like ring
- No decay electron
- Forced 2nd ring ($m_{inv} < 105$ MeV/c^2)
- $E_\nu^{reco} < 1250$ MeV

ν_μ selection

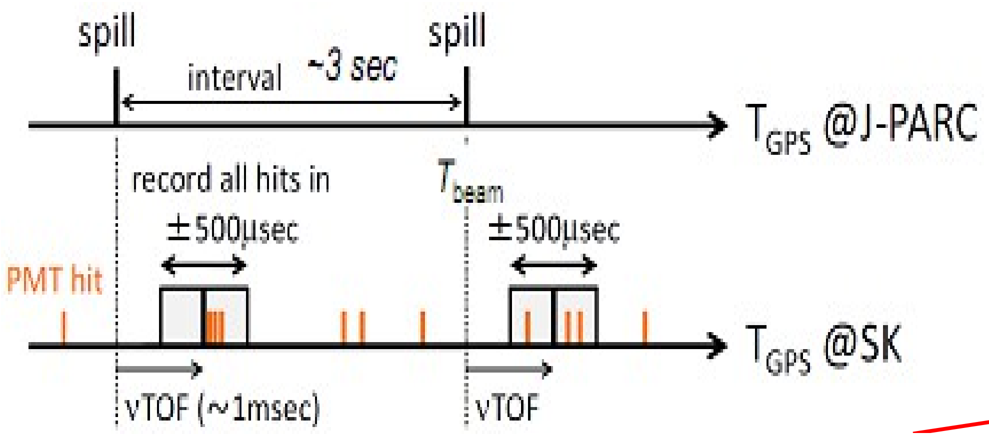
- $E_{vis} > 30$ MeV
- 1 μ-like ring

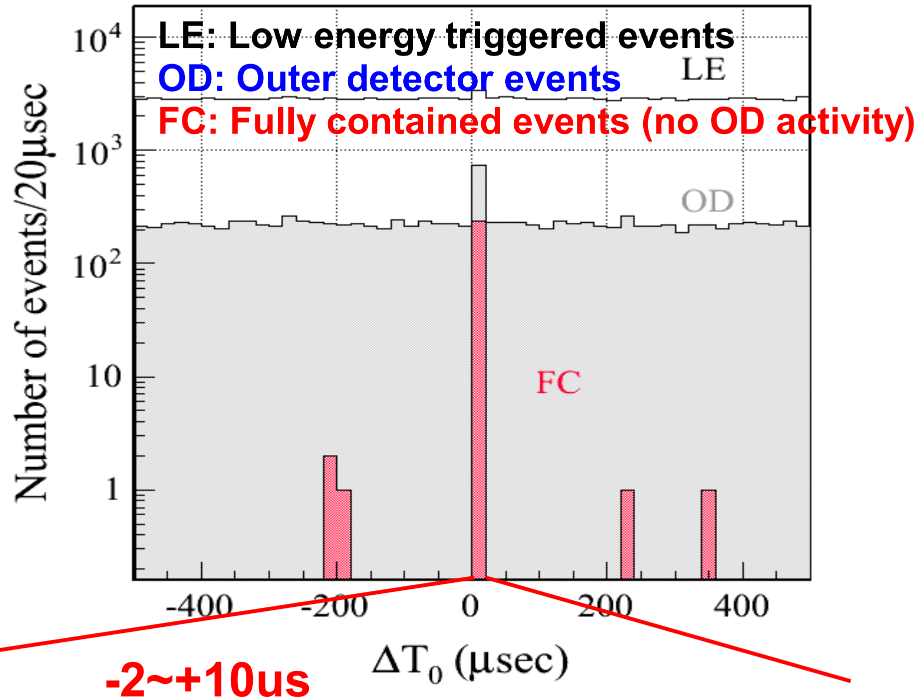
Final ν_e analysis selection

- Unbiased event selection
- Set in advance based previous experience with SK detector and MC study

SK event timing

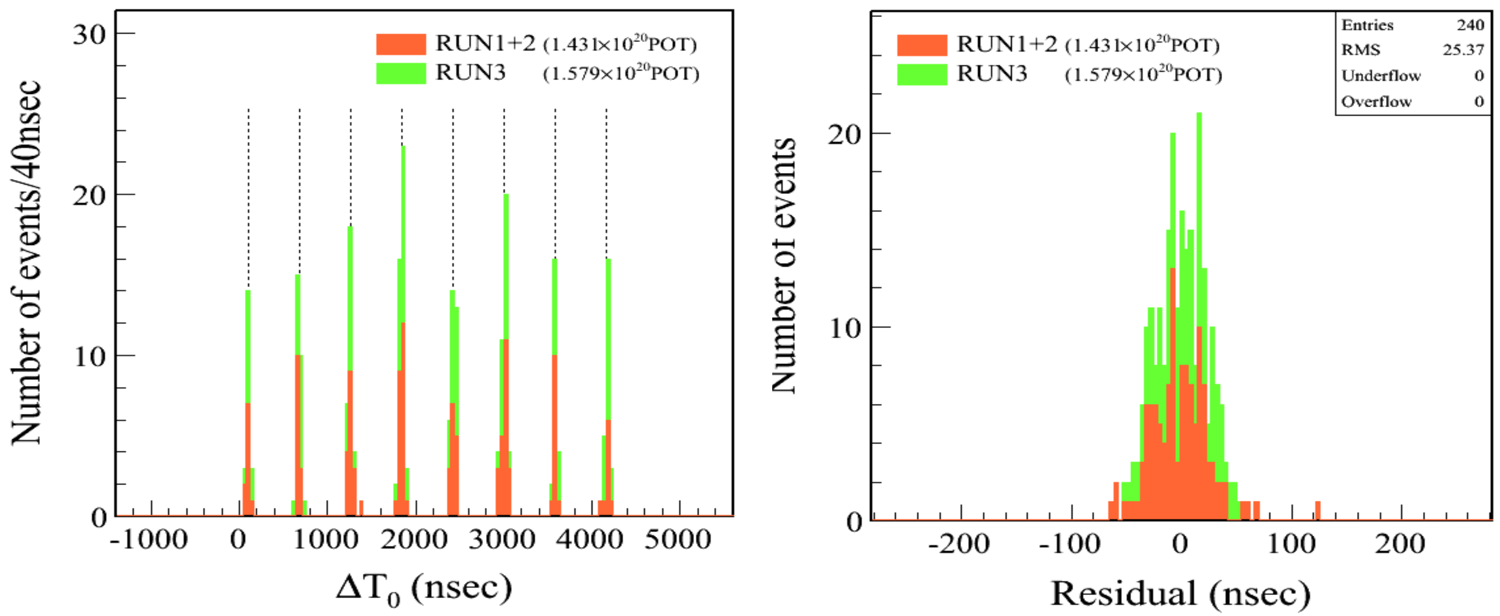
- All hits recorded within +/-500 μs window around beam spill arrival time to SK
- GPS time synchronization





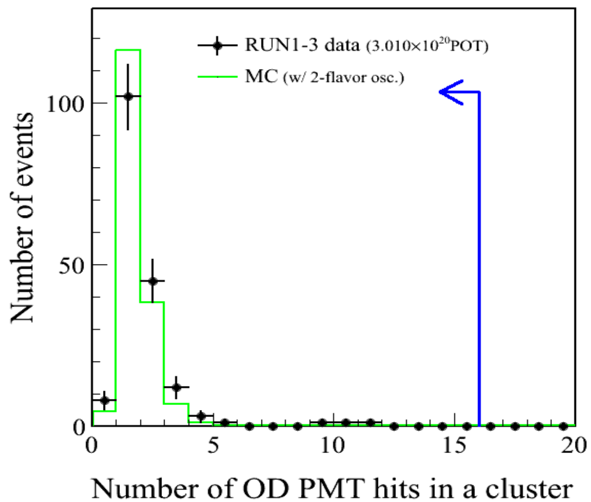
-2~+10us

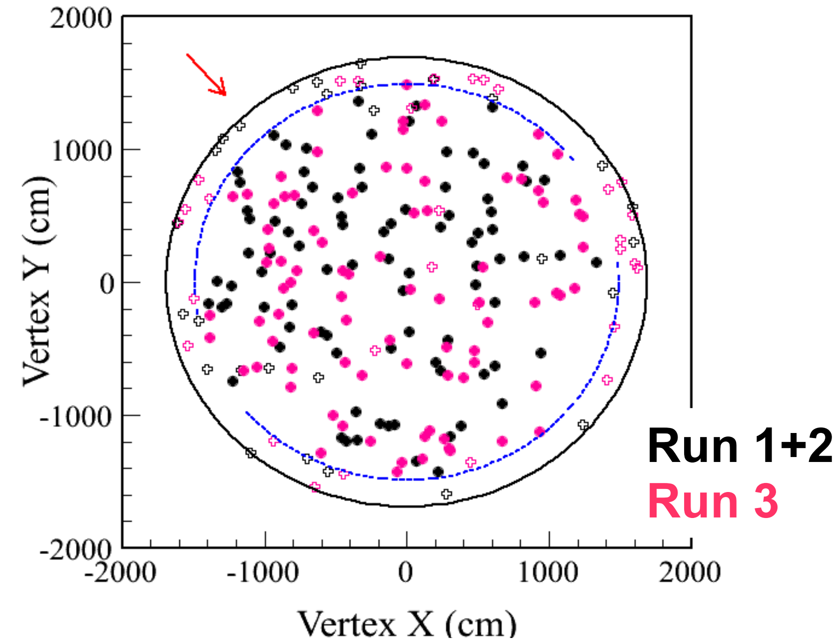
FC events clearly show the beam spill structure

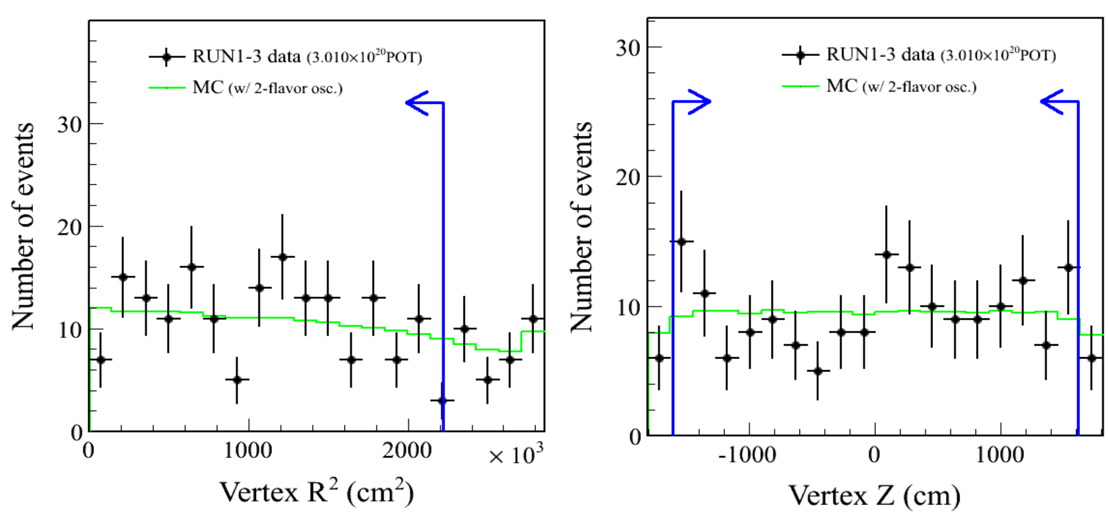


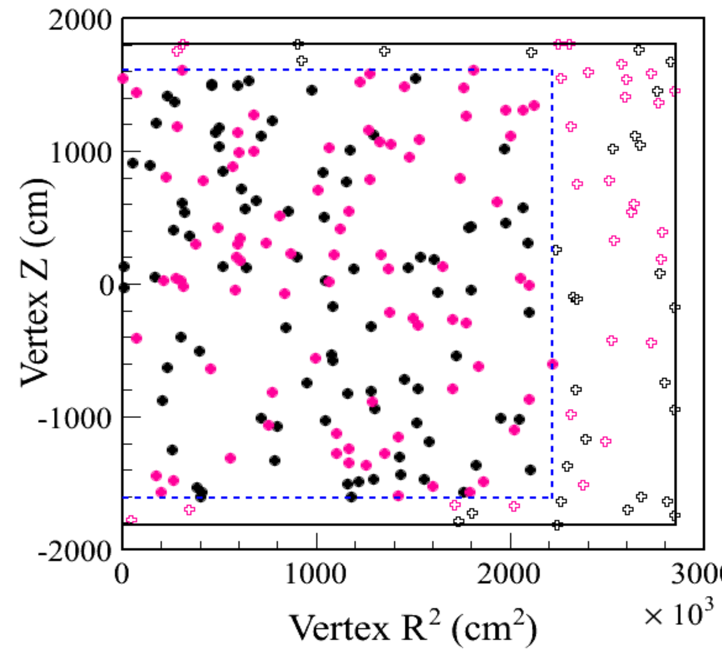
SK selection: FC/FV

- Fully Contained: no OD activity
- Vertex inside Fiducial Volume: 200 cm from the wall

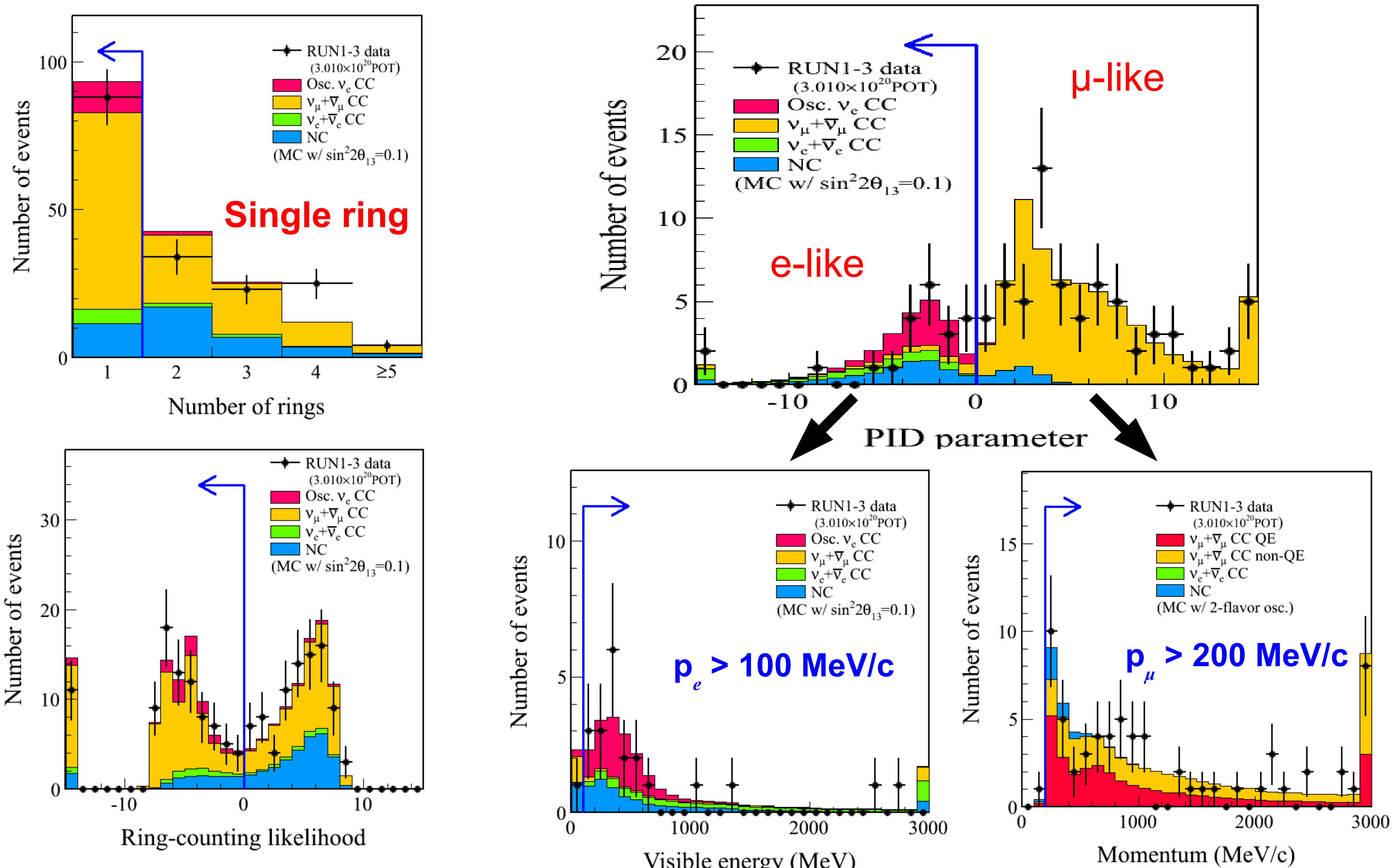








SK selection: ring counting and PID



SK data reduction (so far)

RUN1+2+3 3.010×10^{20}POT	Data	MC Expectations			BG (12μs window)
		$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0$	No osc.	
FC	240	231.6	216.4	465.8	0.039
FCFV	174	163.4	152.7	322.0	0.0048
Single-ring	88	85.6	76.5	222.7	
μ-like (p_μ>200MeV/c)	66 (65)	61.8 (61.4)	61.8 (61.4)	201.4 (200.1)	
e-like (p_e>100MeV/c)	22 (21)	23.8 (21.7)	14.7 (12.8)	21.4 (14.8)	
Multi-ring	86	77.8	76.2	99.2	

Fixed oscillation parameters:

$\Delta m^2_{12} = 7.6\times10^{-5}$ eV^2

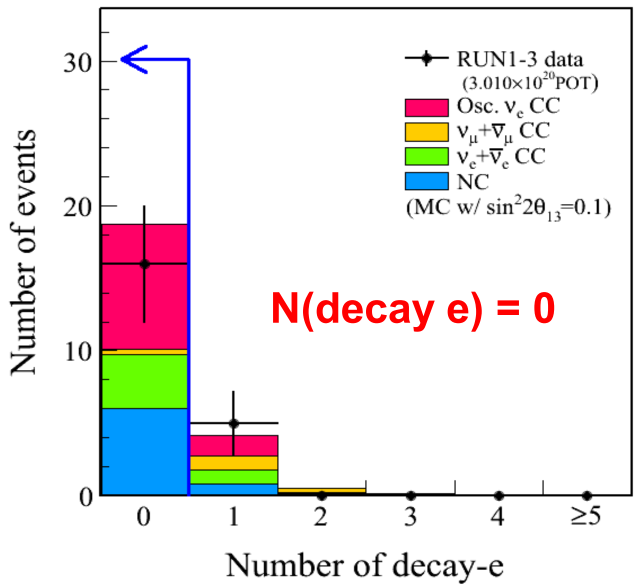
$\Delta m^2_{32} = \pm2.4\times10^{-3}$ eV^2

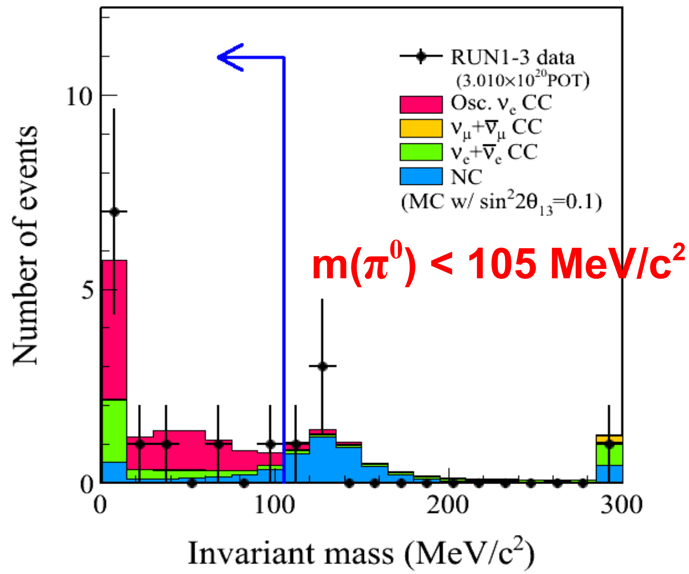
$\sin^2 2\theta_{12} = 0.8704$

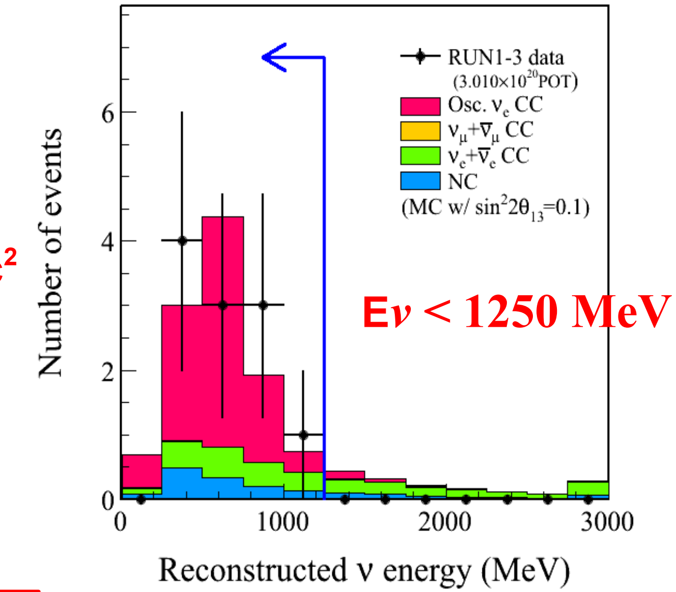
$\sin^2 2\theta_{23} = 1.0$

Nominal MC prediction with 3-flavor oscillation

Final ν_e event selection



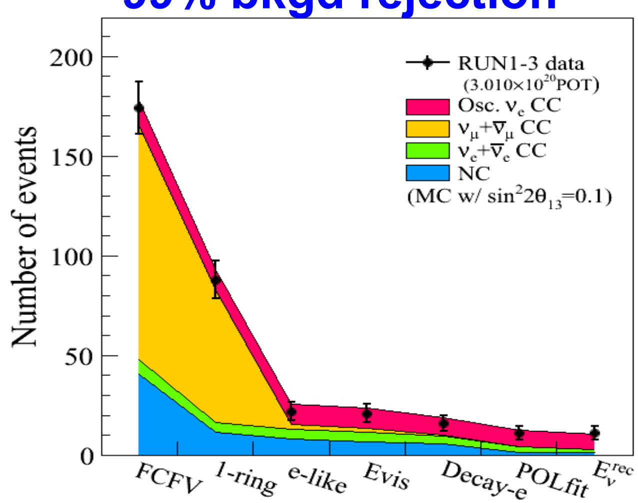


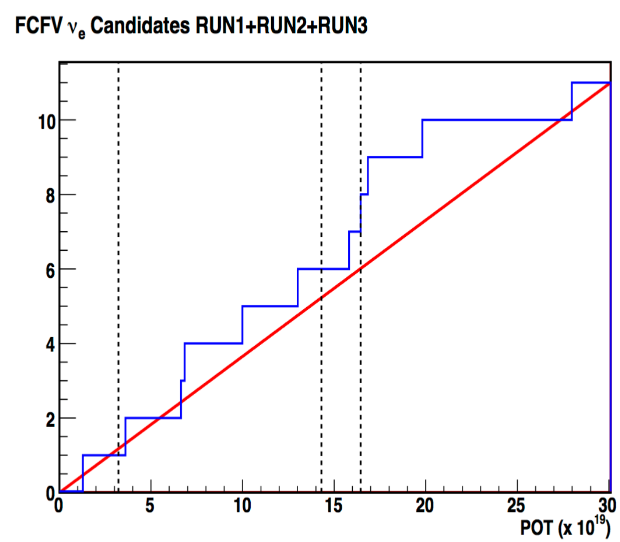


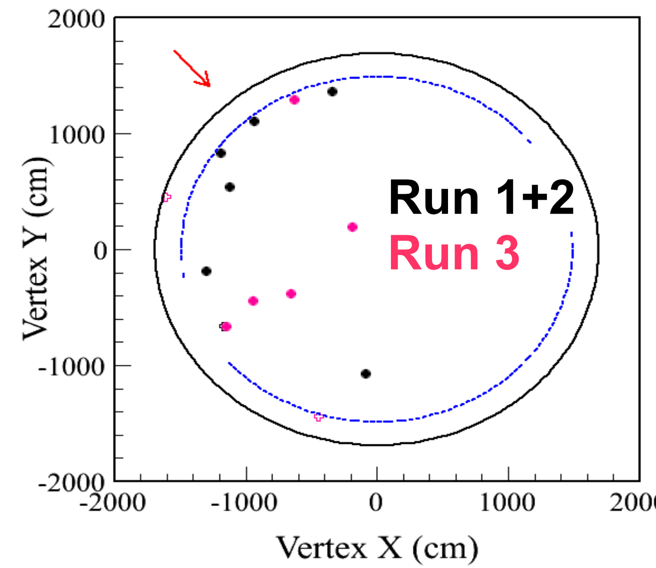
11 ν_e candidates remain

69% signal efficiency

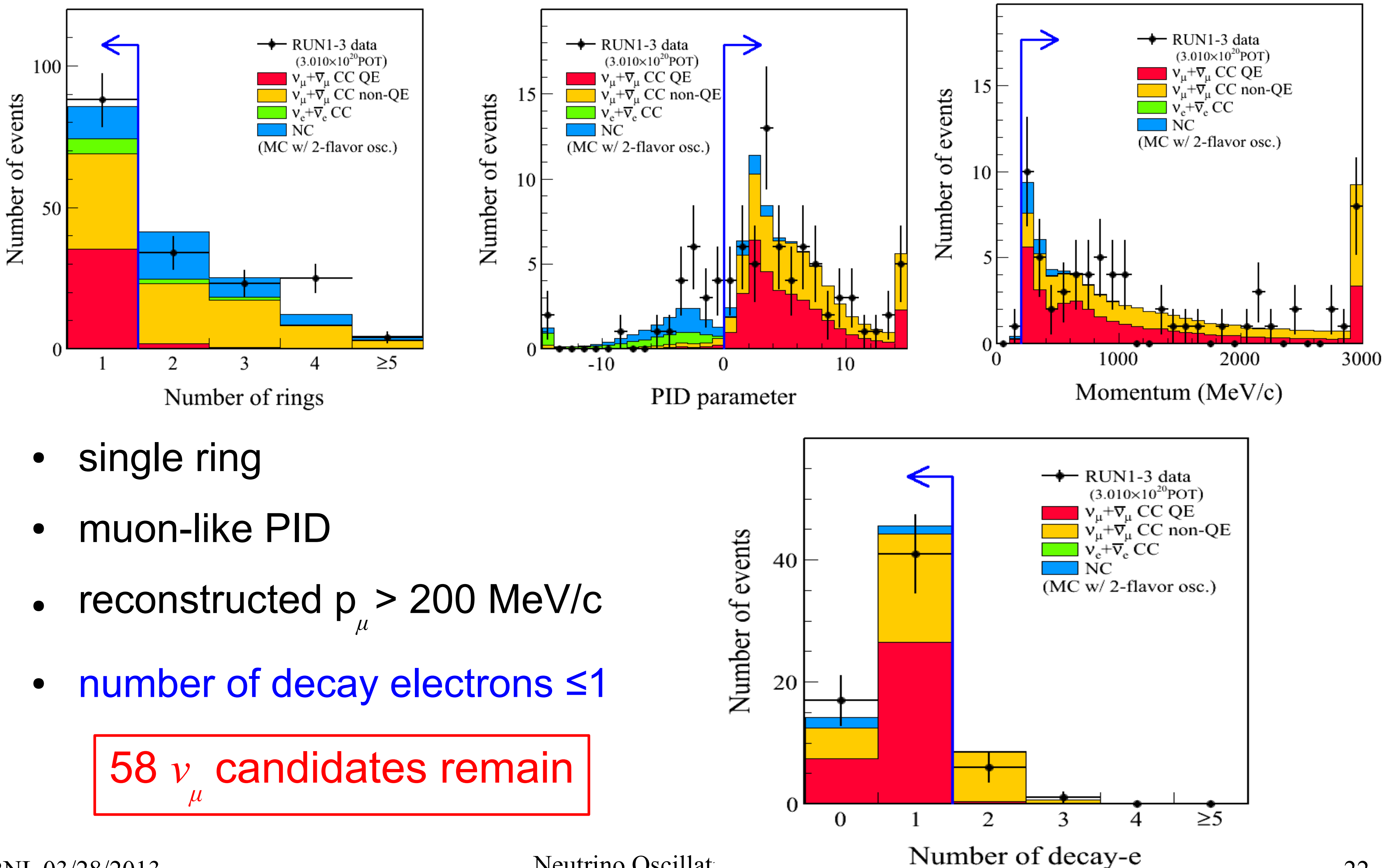
99% bkgd rejection







Final ν_μ event selection



- single ring
- muon-like PID
- reconstructed p_μ > 200 MeV/c
- number of decay electrons ≤1

58 ν_μ candidates remain

Oscillation analysis strategy

ν flux prediction $\Phi(E_\nu)$

Data driven simulation using measurement of proton beam, horn, external hadron production data

ND280 measurement

- ν_μ CCQE and CCnon-QE samples
- Fit data to constrain further flux and cross section parameters

$$N = \Phi(E)\sigma(E)\varepsilon(E)$$

ν cross sections $\sigma(E_\nu)$

Interactions models (NEUT) constrained by external ν and π scattering data

SK measurement

- Predict event rate based on tuned MC simulation

$$N = P(E;o)\Phi(E)\sigma(E)\varepsilon(E)$$

- Fit observed data
- Extract oscillation parameters (o)

ν_e appearance: θ_{13}

ν_μ disappearance: Δm^2_{32}, θ_{23}

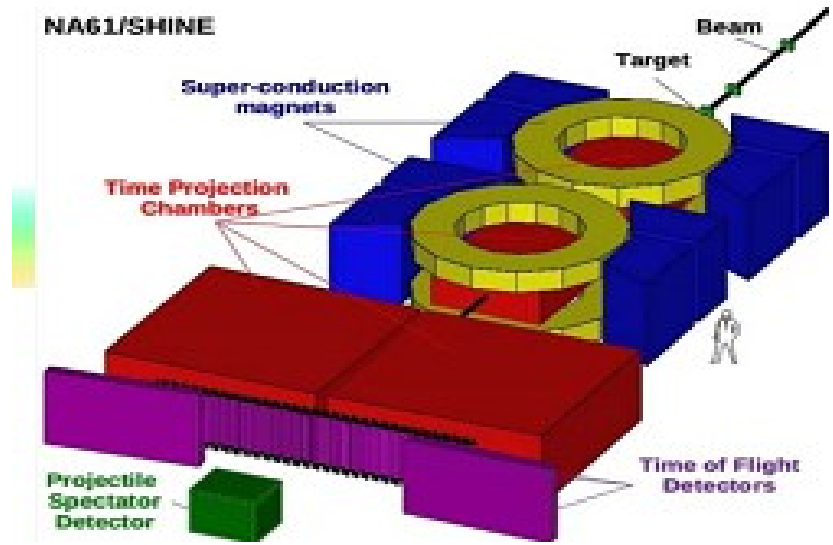
$\Phi(E)$ and $\sigma(E)$ are not the same at the near and far detectors, but they are correlated through the underlying processes

Flux tuning

Start with FLUKA/GEANT3 based beam simulation

Prediction tuned and constrained by

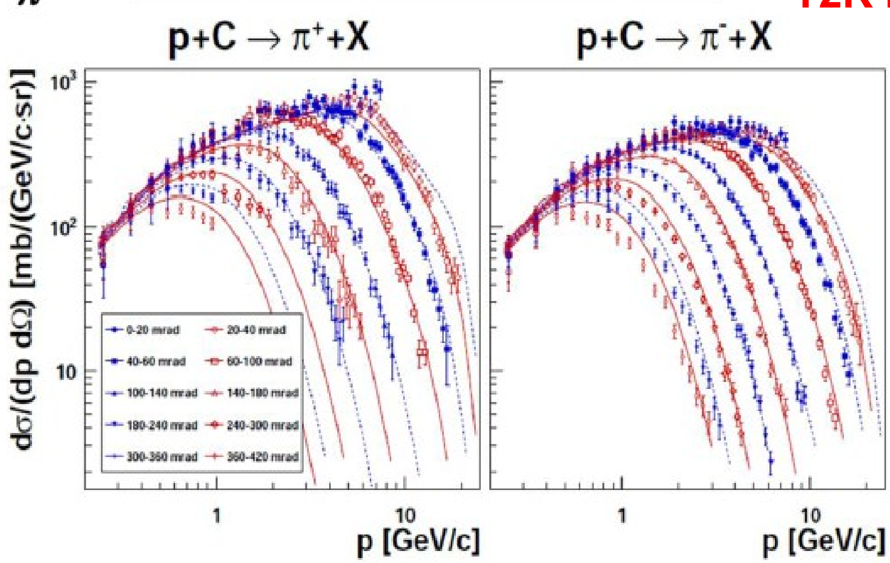
- in-situ measurements of p beam, horn current and field, alignment, etc.
- external hadron production measurements (in particular NA61 at CERN)



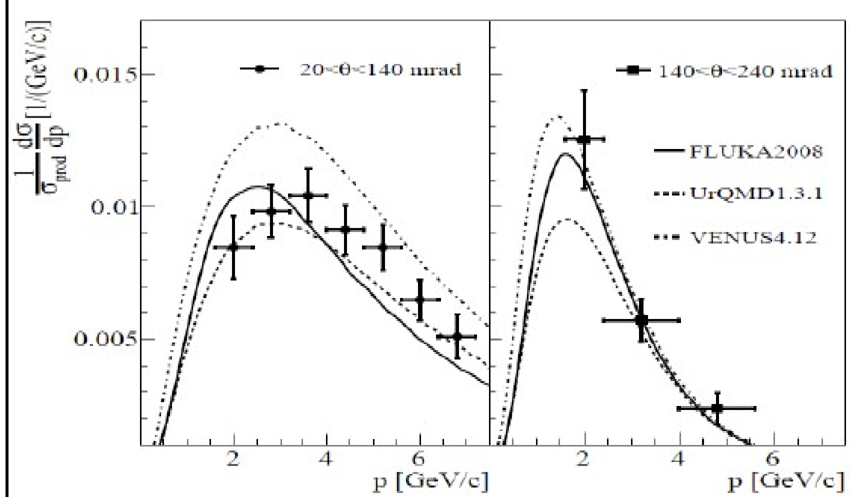
σ_{prod} (pC@31GeV/c)= 229.3 ± 1.9 ± 9.0 (mb)

$\pi^{\pm}$ *Phys. Rev. C 84 (2011) 034604*

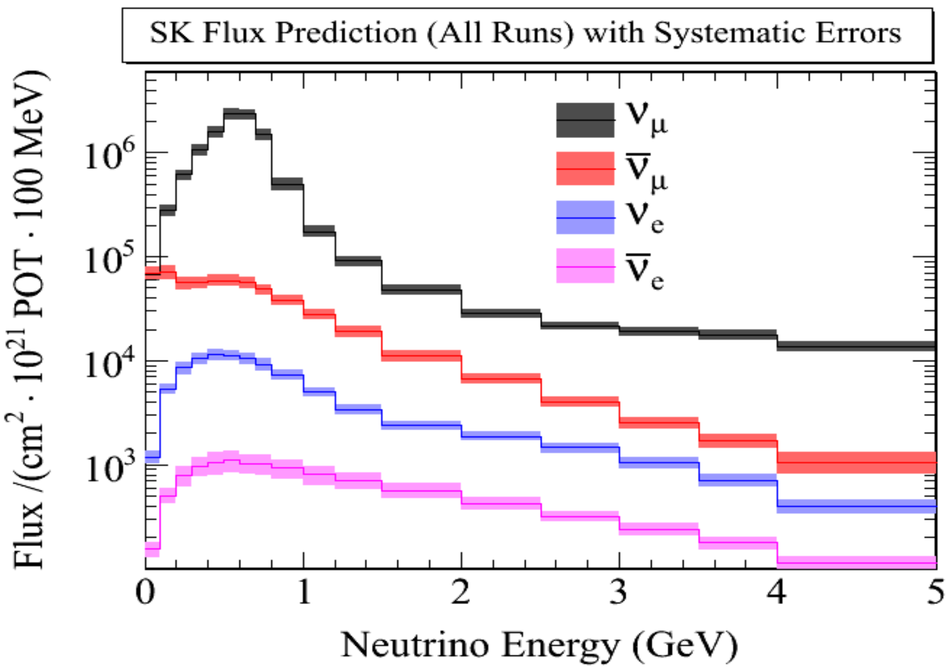
T2K replica target

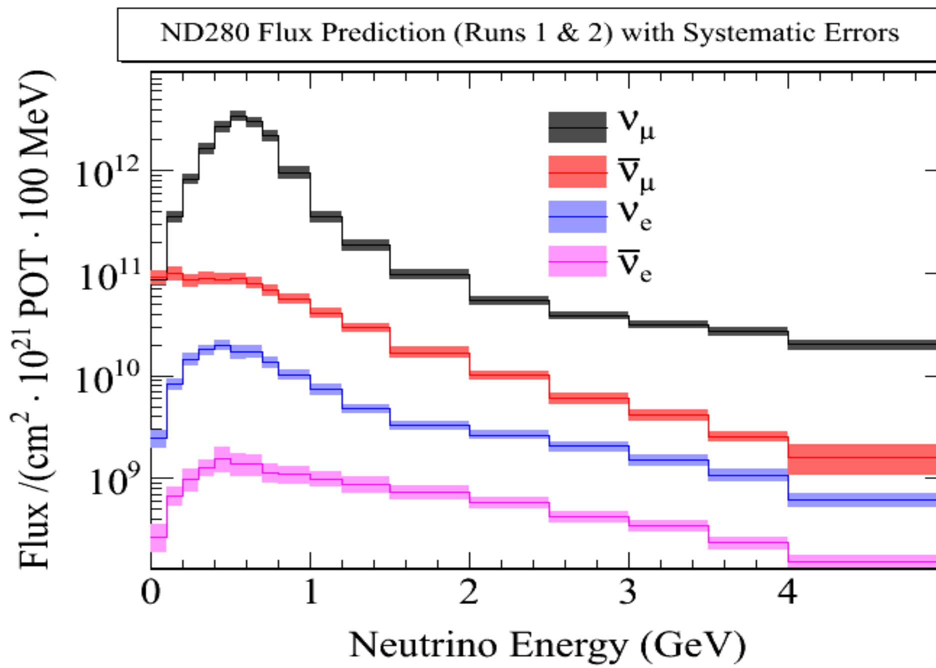


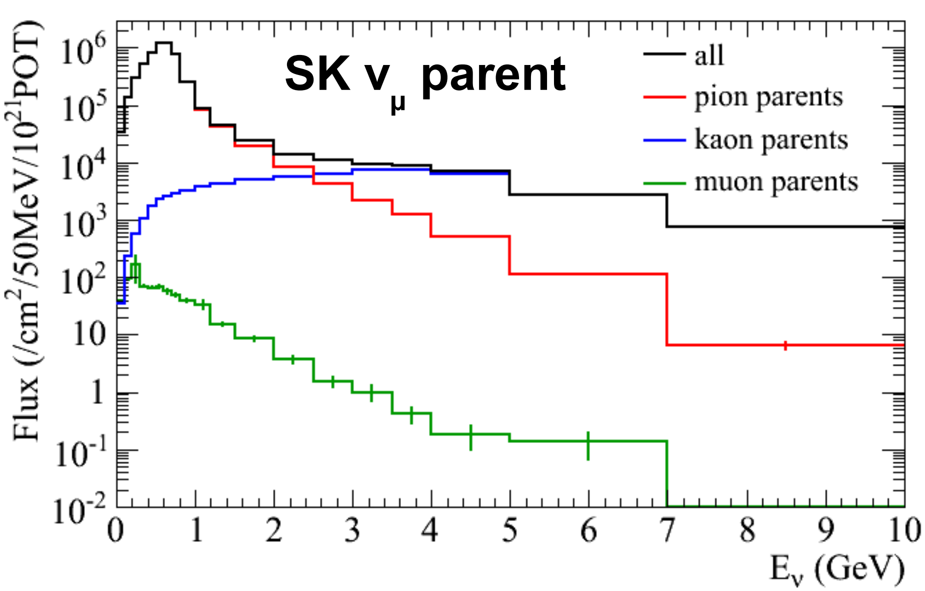
K^+ *Phys. Rev. C 85 (2012) 035210*

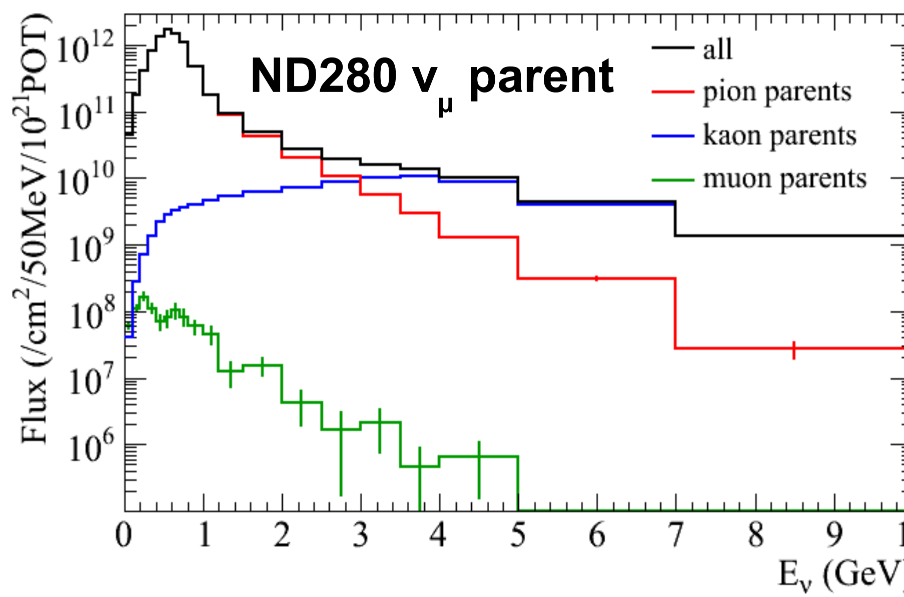


Flux prediction

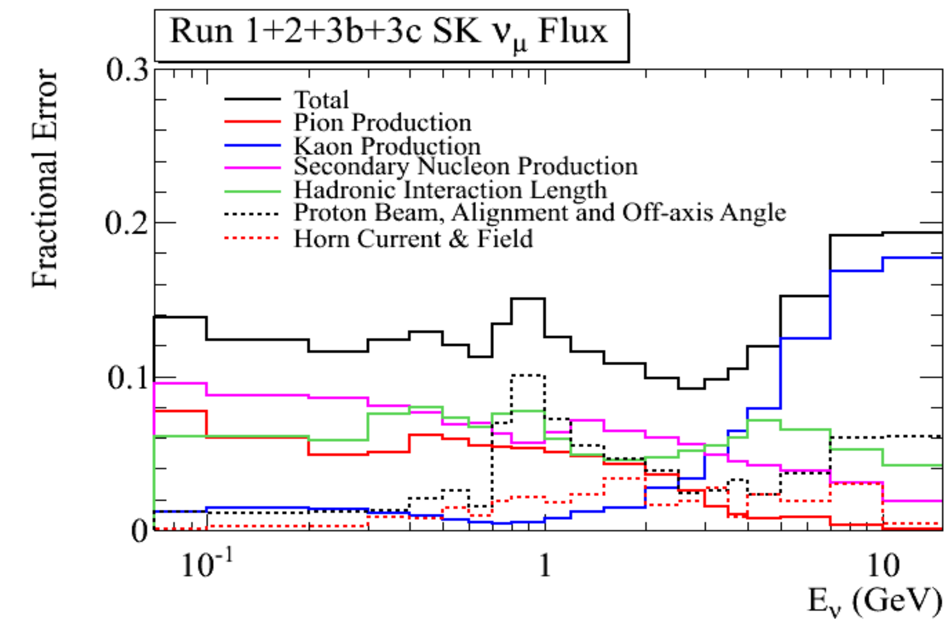


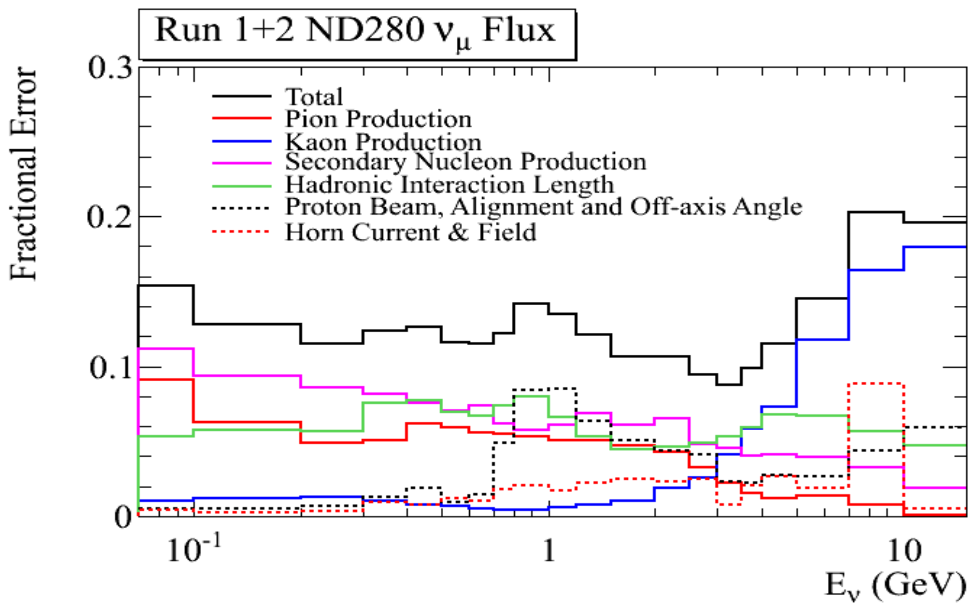




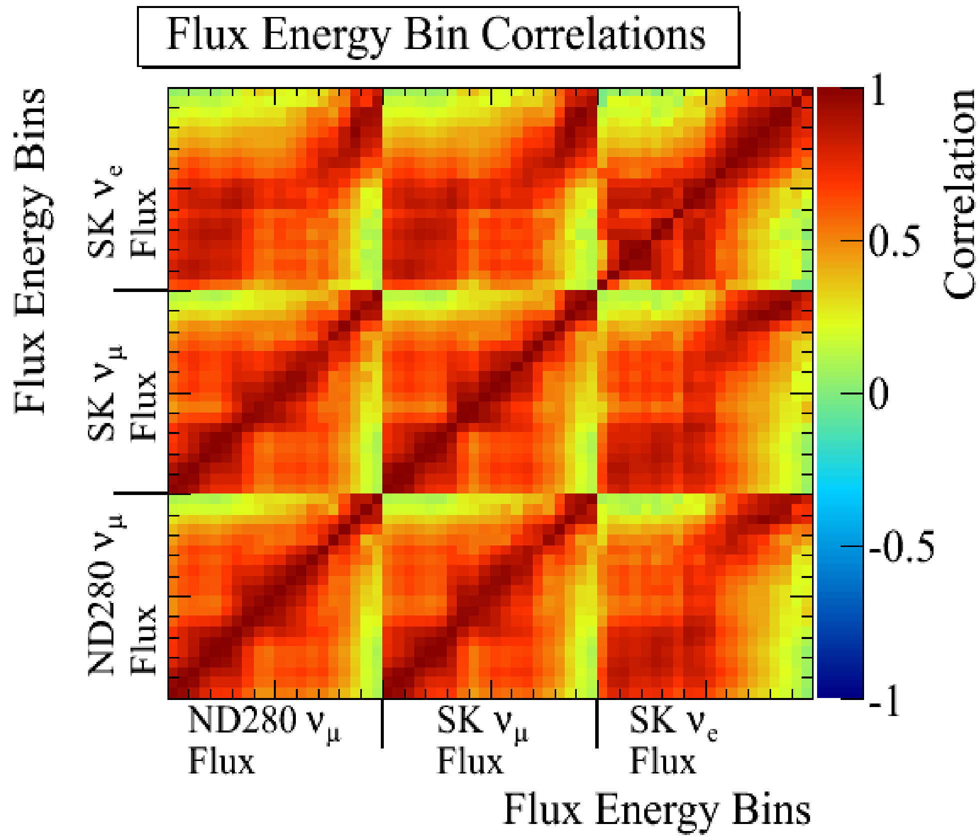


Flux uncertainty

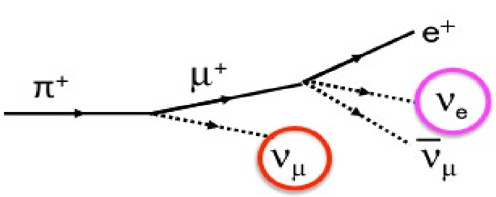




- 10-15% errors (before ND280 fit)



- Correlations in the flux covariance due to shared hadron production



ν interaction tuning

- NEUT (GENIE) simulation incorporates basic nu interaction models (Elastic, QE, Resonance/Coherent π, DIS) + final state interaction (FSI) model
- Uncertainties are described by a combination of normalization and model parameters, or incorporated into detector systematics

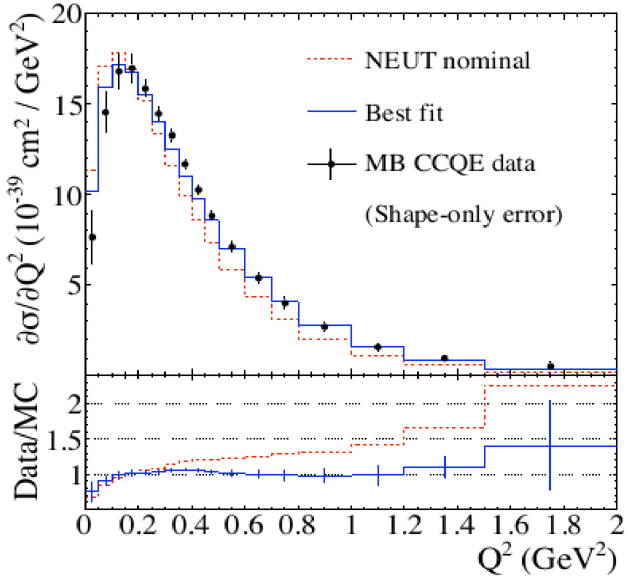
QE1 $0<E_\nu<1.5$ GeV	normalization
QE2 $1.5<E_\nu<3.5$ GeV	normalization
QE3 $E_\nu>3.5$ GeV	normalization
CC1π $E_\nu<2.5$ GeV	normalization
CC1π $E_\nu>2.5$ GeV	normalization
NC1π^0	normalization
M_A^{QE}	axial mass (QE)
M_A^{RES}	axial mass (1π)
pF	Fermi momentum
E_B	binding energy
Spectral Function	model comparison
CC other	uncertainty
CC Coherent	uncertainty

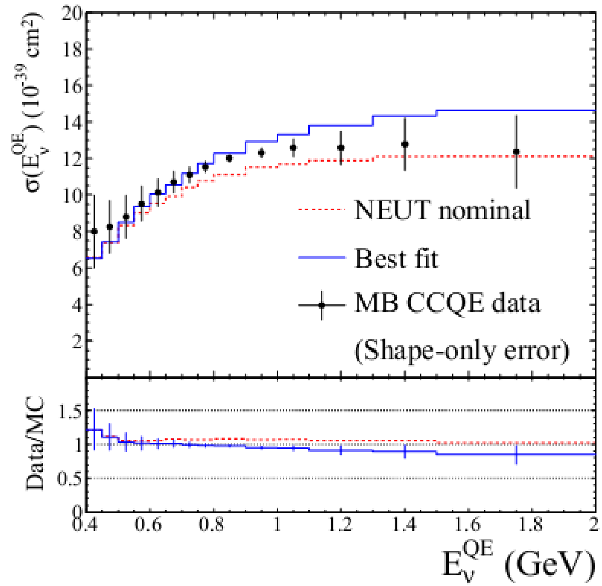
Parameters are tuned to and constrained by external (ν and π scattering) data or alternative models:

- MiniBooNE CC1π and CCQE data
- NOMAD CCQE data at high energy
- K2K (CC1π^0, CC-coherent) and SciBooNE (CC/NC-coherent) data used as cross check
- Pion scattering data used to tune/constrain FSI model parameters

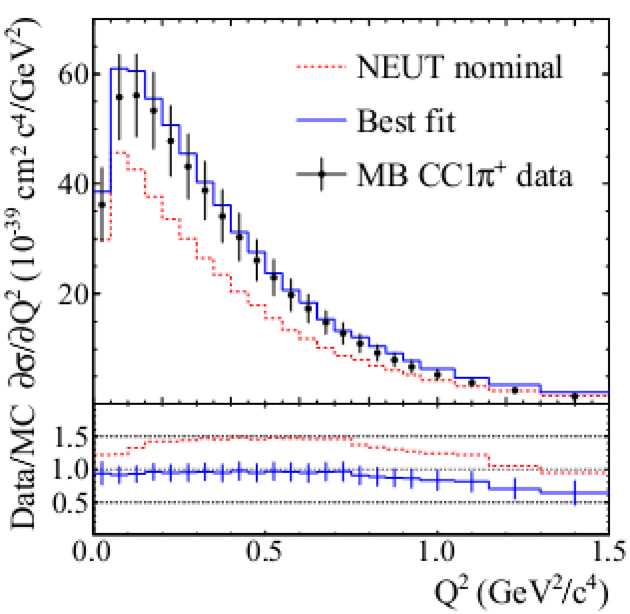
ν cross section tuning

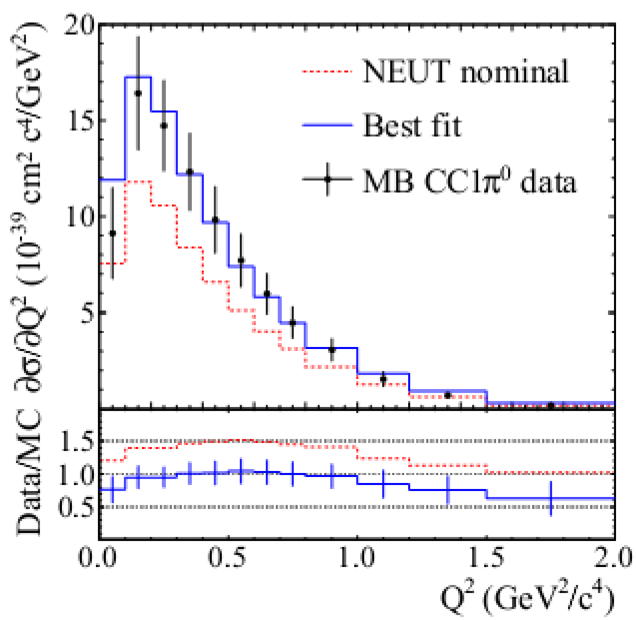
Fit to MiniBooNE CCQE data: large discrepancy sets uncertainty on M_A^{QE}

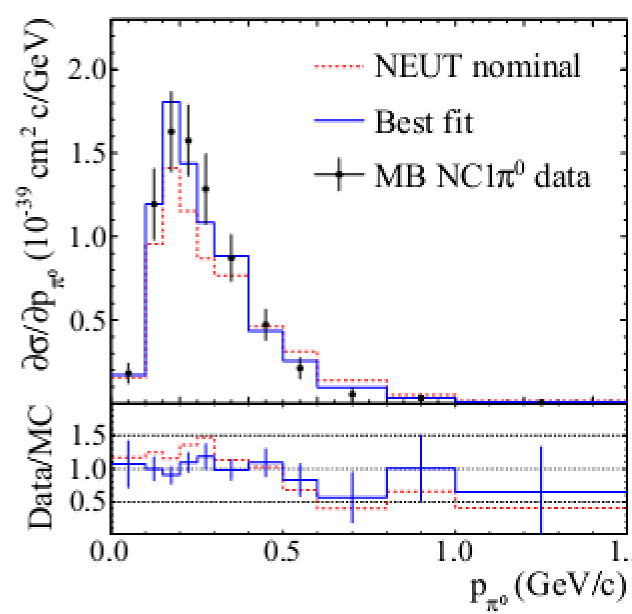




Simultaneous fit of MiniBooNE CC1π and NCπ^0 data: constraint on M_A^{RES}, CC1π norm (<2.5 GeV) and NC1π^0 norm





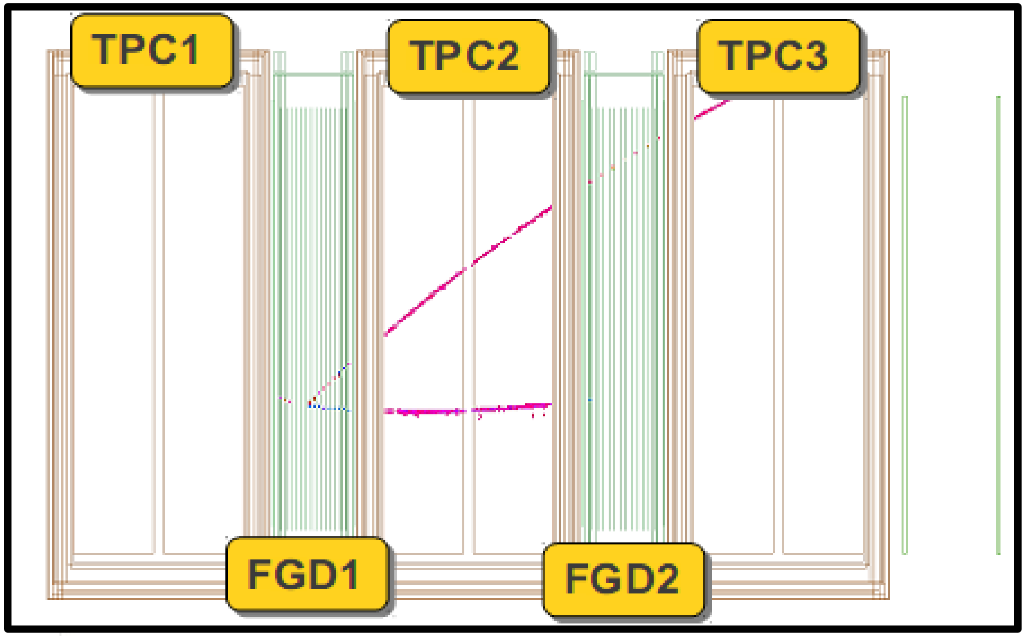


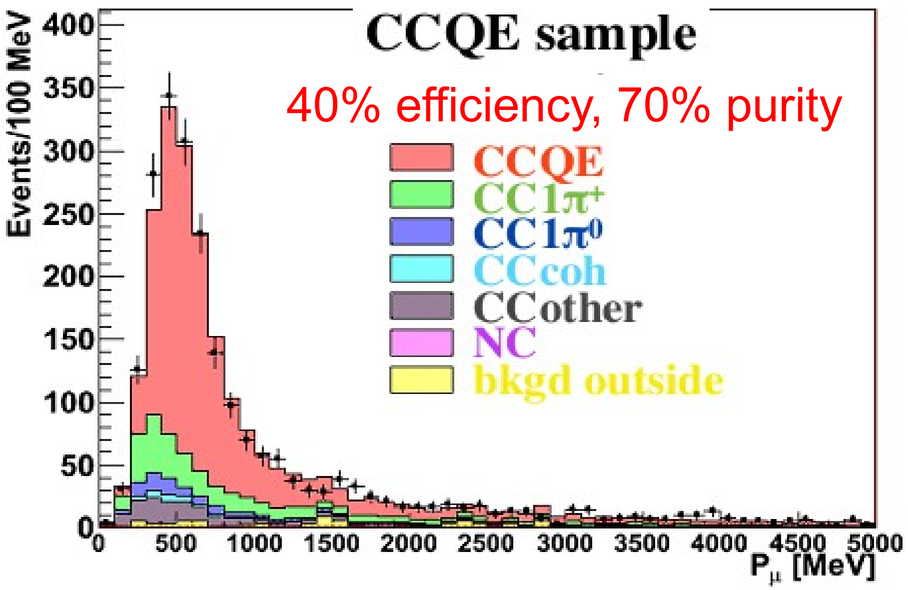
ND280 ν_μ CC event selection (Run 1+2)

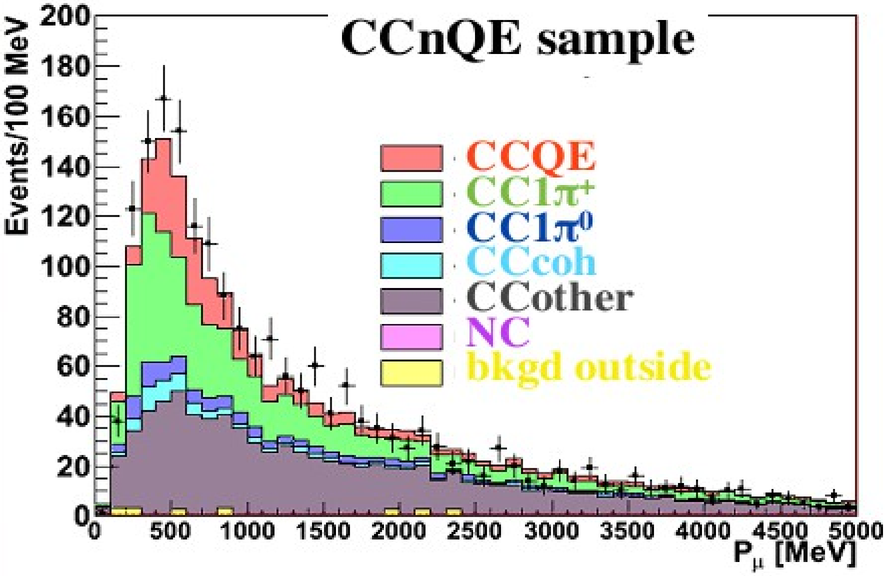
- Good negative track starting in FGD1
- Muon ID based on energy loss in TPC
- Upstream TPC veto

Divided into two sub-sets:

- CCQE-like: only 1 FGD-TPC track and no Michel electron (in FGD1)
- CC non-QE-like







ND280 likelihood

- Binned likelihood of the data in (p_μ,θ_μ) combined with the prior constraints on the ν flux, ν interaction, and detector systematics

$$-2lnL = 2\sum_i^{p,\theta\ bins} N_i^{pred}(\vec{f},\vec{x},\vec{d}) - N_i^{data} + N_i^{data} ln[N_i^{data}/N_i^{pred}(\vec{f},\vec{x},\vec{d})]$$

$$+ \sum_j^{E_\nu\ bins}\sum_k^{E_\nu\ bins}(1-f_j)(V_f^{-1})_{j,k}(1-f_k)$$

$$+ \sum_l^{xsec\ pars}\sum_m^{xsec\ pars}(x_{nom}-x_l)(V_x^{-1})_{l,m}(x_{nom}-x_m)$$

$$+ \sum_i^{p,\theta\ bins}\sum_n^{p,\theta\ bins}(1-d_i)(V_d^{-1})_{i,n}(1-d_n)$$

$$+ ln\left(\frac{|V_d(\vec{f},\vec{x})|}{|V_d^{nom}|}\right)$$

ND280 constraint
$ln\ L_{ND280}(\vec{f},\vec{x},\vec{d}\,)$

+

Neutrino flux term
$ln\ L_{flux}(\vec{f}\,)$

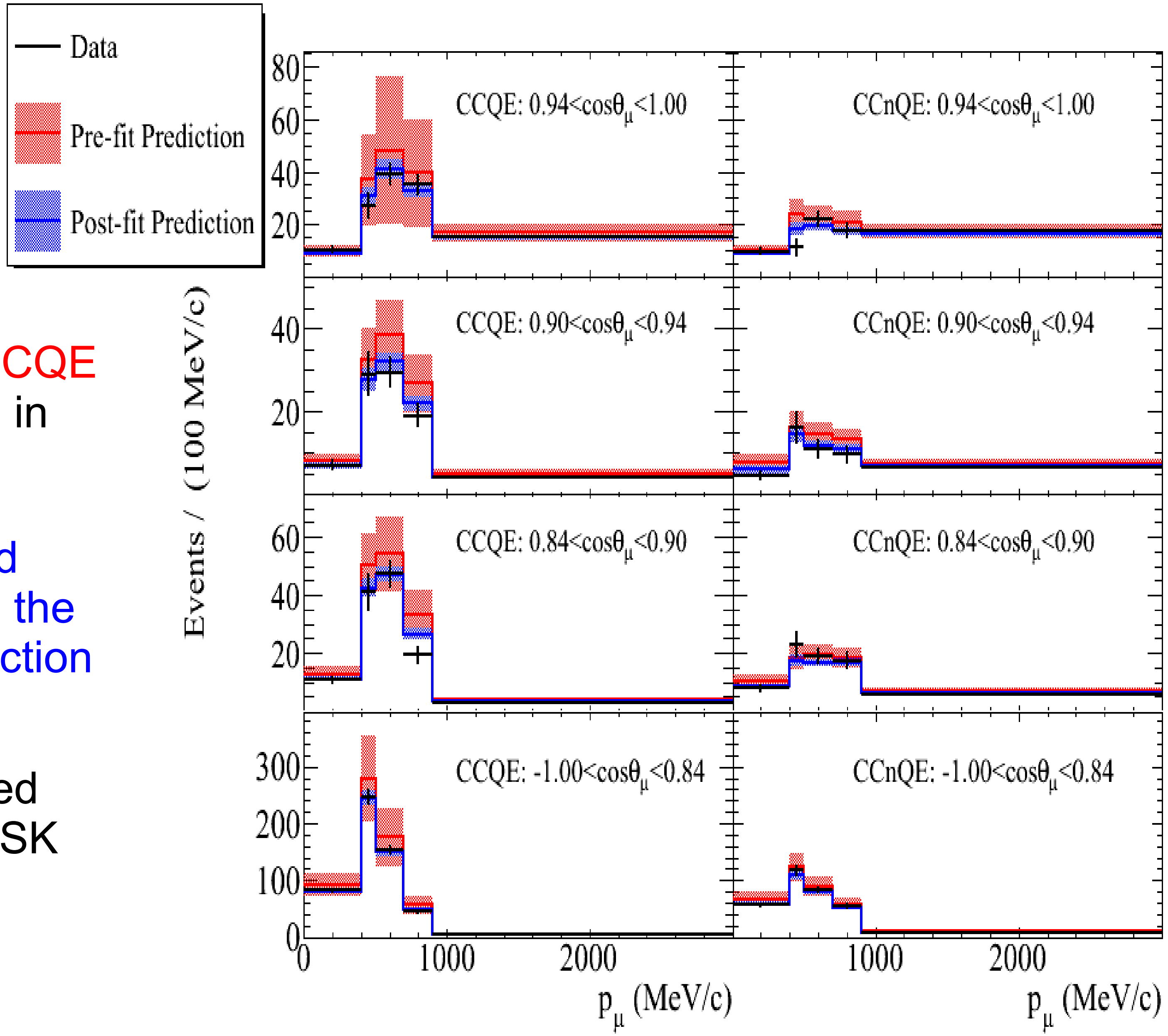
+

Neutrino xsec term
$ln\ L_{xsec}(\vec{x}\,)$

+

Det systematics + FSI
$ln\ L_{det}(\vec{d})$

Fit to ND280 data



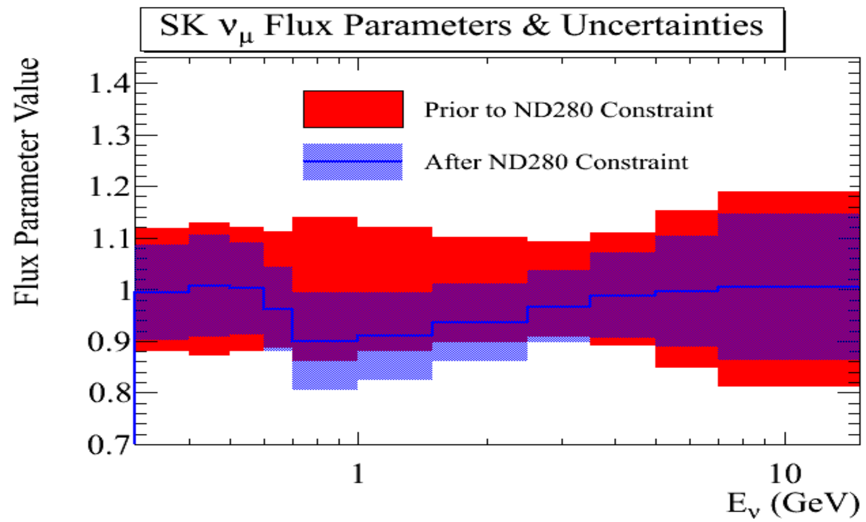
Simultaneous fit to the CCQE and CCnQE data binned in *(p_μ,θ_μ)*

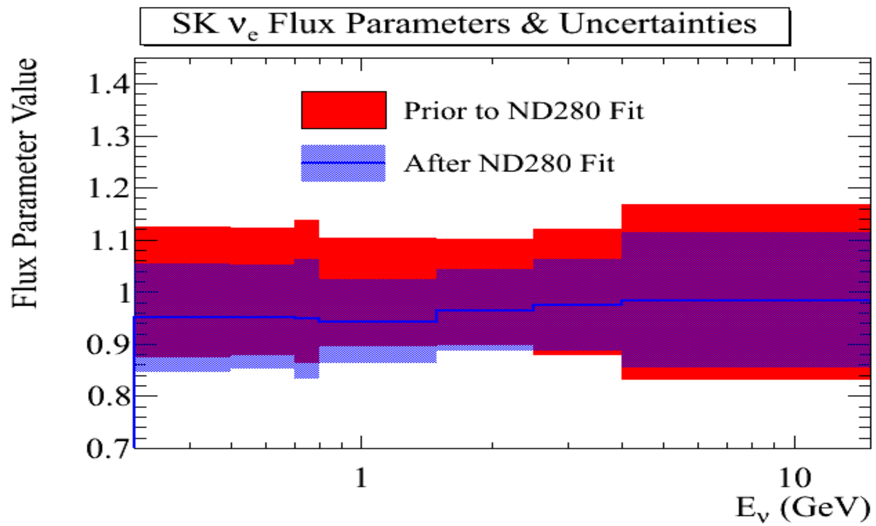
Maximizing the combined likelihood with respect to the flux and shared cross section parameters

Marginalizing uncorrelated parameters b/w ND and SK

Systematic parameters after fit

- Flux and cross section parameters slightly change after to the ND fit
- Uncertainties are significantly reduced



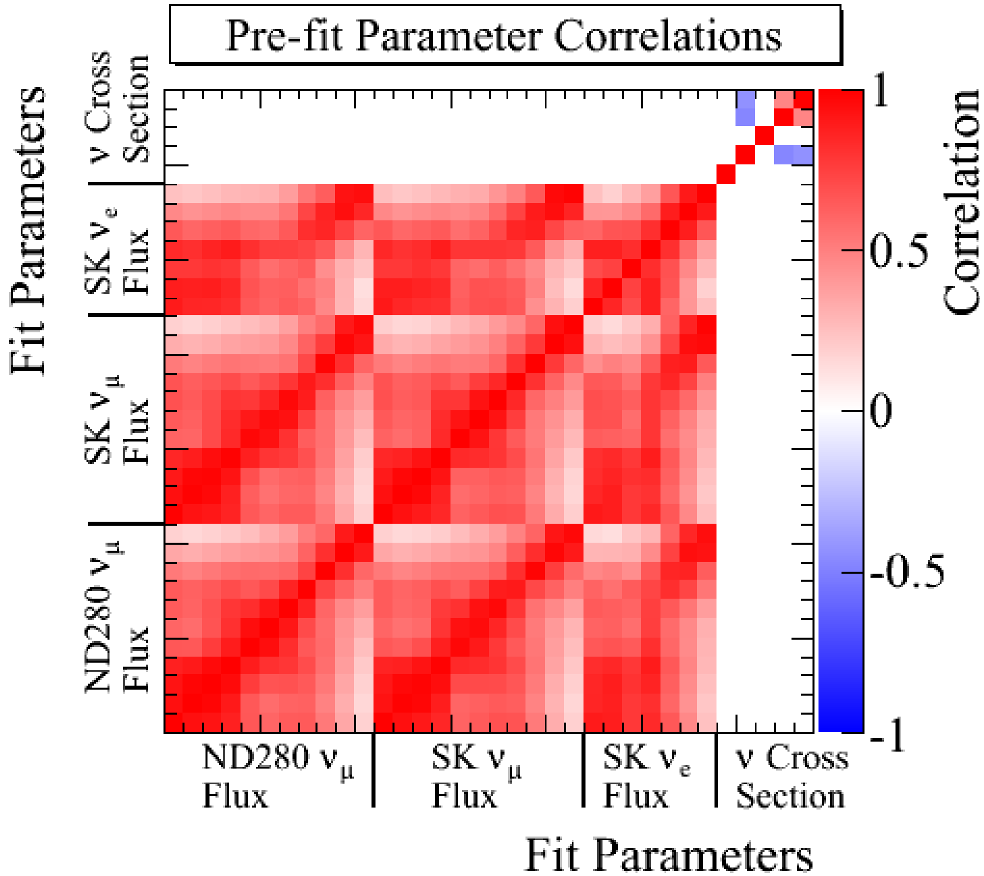


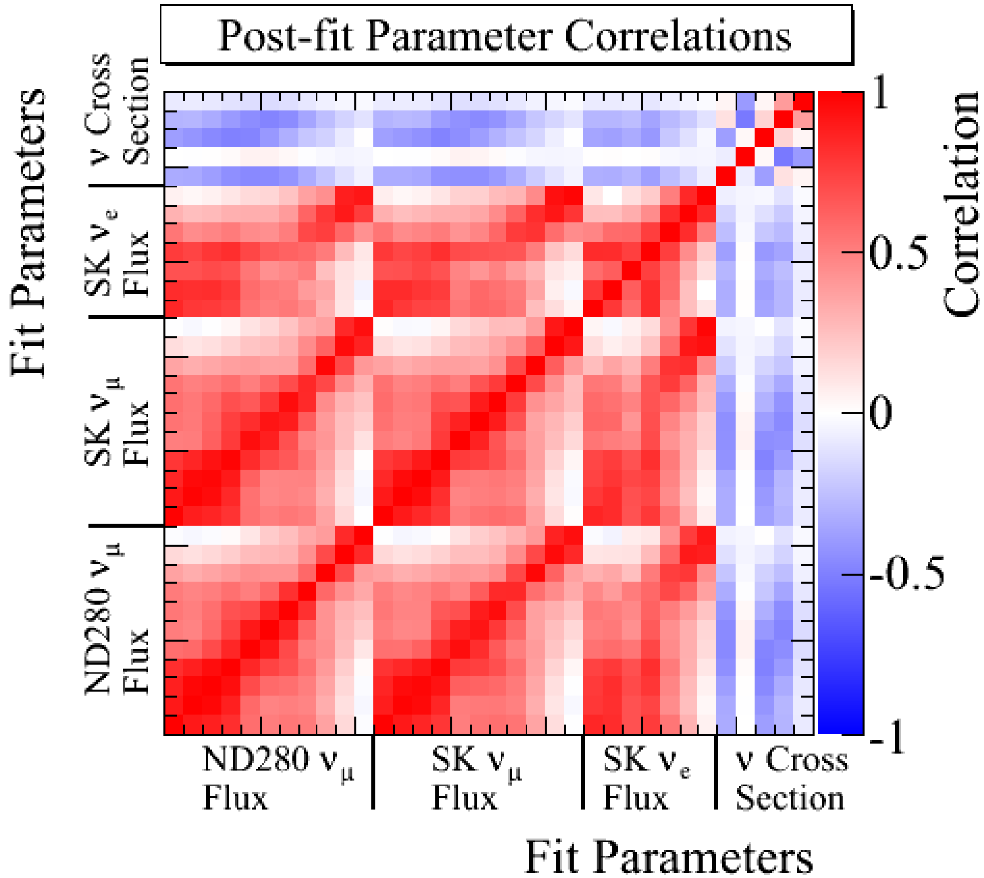
	Before fit	After fit
M_A^{QE} (GeV)	1.21 ± 0.45	1.19 ± 0.19
M_A^{RES} (GeV)	1.162 ± 0.110	1.137 ± 0.095
CCQE Norm. 0-1.5 GeV	1.000 ± 0.110	0.941 ± 0.087
CCQE Norm. 1.5-3.5 GeV	1.00 ± 0.30	0.92 ± 0.23
CCQE Norm. >3.5 GeV	1.00 ± 0.30	1.18 ± 0.25
CC1π Norm. 0-2.5 GeV	1.63 ± 0.43	1.67 ± 0.28
CC1π Norm. >2.5 GeV	1.00 ± 0.40	1.10 ± 0.30
NC1π^0 Norm.	1.19 ± 0.43	1.22 ± 0.40
Fermi Momentum (MeV/c)	217 ± 30	224 ± 24
Spectral Function	0(off) ± 1(on)	0.04 ± 0.21
CC Other Shape (GeV)	0.00 ± 0.40	-0.05 ± 0.35

Parameter value, uncertainty is determined from MiniBooNE single pion samples

Parameter value, uncertainty is extrapolated to SK sample

Correlation matrix

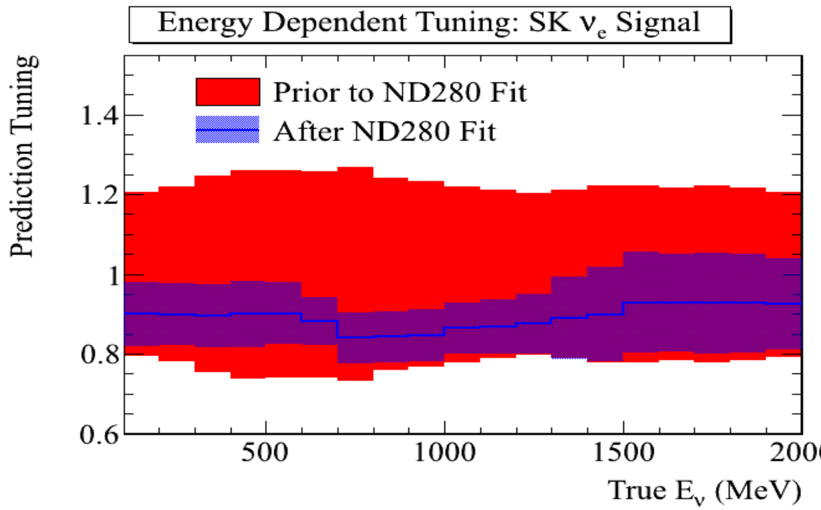




- The fit also modifies the correlations between parameters:
  - the flux normalizations become more diagonal
  - flux and shared cross section parameters become (anti-) correlated

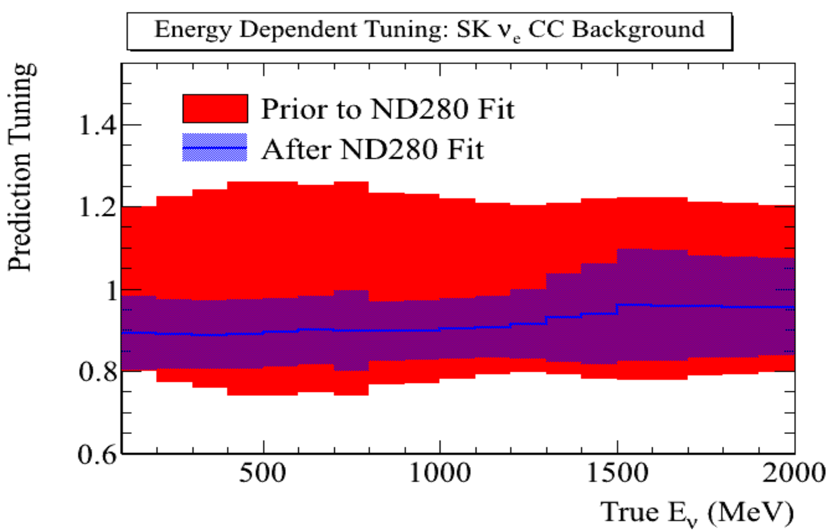
Predicted far detector ν_e event rate

- Ratio of signal (background) prediction before/after the ND280 fit

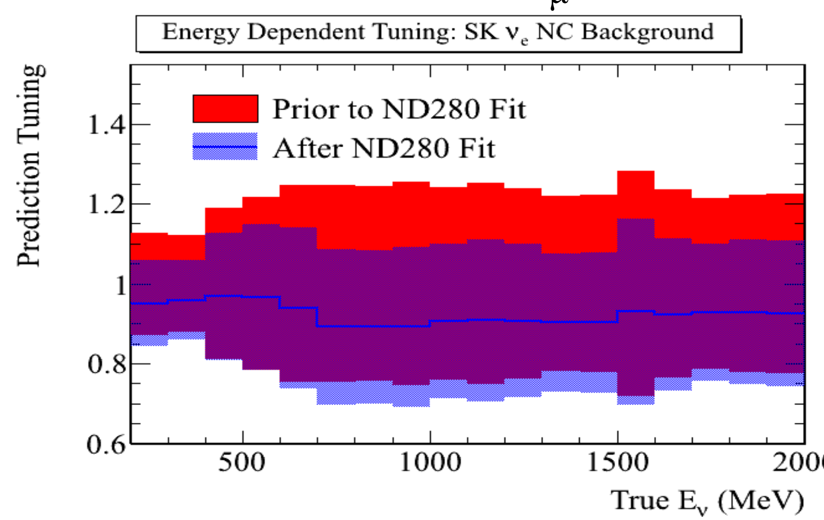


ν_e signal

ν_e CC background



ν_μ NC background



band represents the error from flux + shared cross section

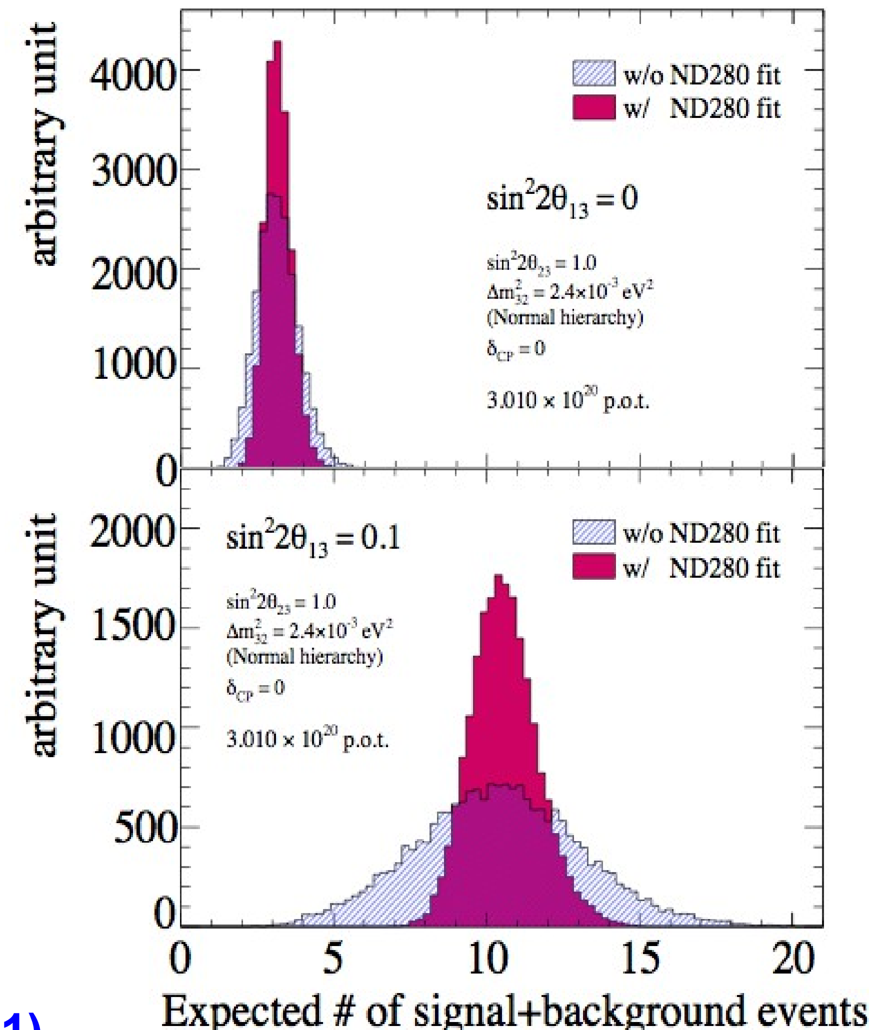
Predicted far detector ν_e events

- ND280 constraint reduces systematic uncertainty significantly

Event category	The predicted number of events $\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22	10.71
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background	1.21	1.21
$\bar{\nu}_\mu$ background	0.07	0.07
$\bar{\nu}_e$ background	0.09	0.09

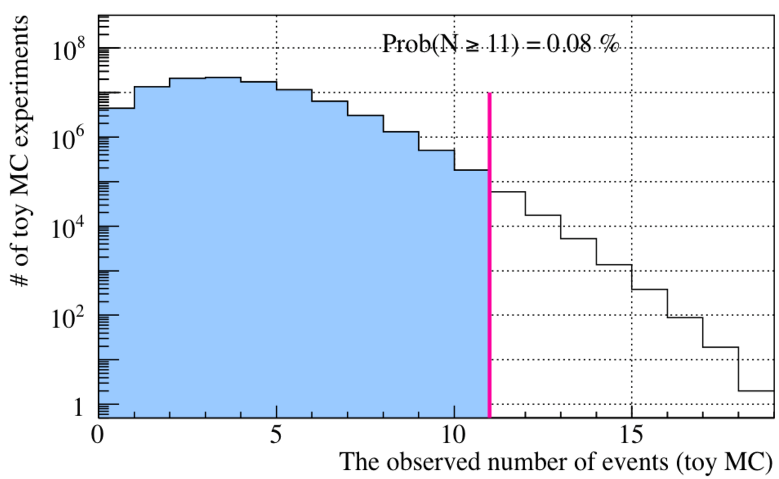
Uncertainties	ν_e bkrd	ν_e sig+bkrd
ν flux+xsec (constrained by ND280)	±8.7%	±5.7%
ν xsec (unconstrained by ND280)	±5.9%	±7.5%
Far detector	±7.7%	±3.9%
Total	±13.4%	±10.3%
No ND measurement	26%	22%

18% (2011) normalization only



Significance of ν_e signal

RUN 1+2+3 3.010×10^{20} POT	Data	MC Expectation w/ $\sin^2 2\theta_{13}=0.1$				
		Signal $\nu_\mu \to \nu_e$	BG total	CC ($\nu_\mu+\bar{\nu}_\mu$)	CC($\nu_e+\bar{\nu}_e$)	NC
Fully contained FV at beam timing	174	12.35	165.47	117.33	7.67	40.48
Single ring	88	10.39	82.78	66.41	4.82	11.55
e-like	22	10.27	15.60	2.72	4.79	8.10
E_{vis}>100MeV	21	10.04	13.53	1.76	4.75	7.01
No decay-e	16	8.63	10.09	0.33	3.76	6.00
2γ invariant mass cut	11	8.05	4.32	0.09	2.60	1.64
E_ν^{rec} < 1250 MeV (MC $\sin^2 2\theta_{13}=0$ case)	11	7.81 (0.18)	2.92 (3.04)	0.06 (0.06)	1.61 (1.73)	1.25 (1.25)
Efficiency [%]		60.7	1.0	0.0	20.0	0.9



11 events observed

Expected bckg: 3.22 ± 0.43 (θ_{13} = 0)

p=0.08% (3.2σ)

Clear evidence for ν_e appearance!

ν_e appearance fit

Extended maximum likelihood fit to extract $\sin^2 2\theta_{13}$

$$\mathcal{L}(N_{obs.}, \boldsymbol{x}; \boldsymbol{o}, \boldsymbol{f}) = \mathcal{L}_{norm}(N_{obs.}; \boldsymbol{o}, \boldsymbol{f}) \times \mathcal{L}_{shape}(\boldsymbol{x}; \boldsymbol{o}, \boldsymbol{f}) \times \mathcal{L}_{syst.}(\boldsymbol{f})$$

measurement variables

oscillation parameter

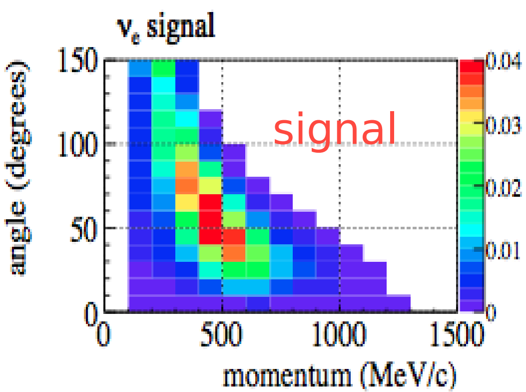
systematic parameters (prior: ND280 results)

3 analysis methods:

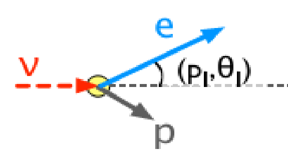
- rate + (p_e,θ_e) shape
- rate + E_ν^{reco}
- rate only

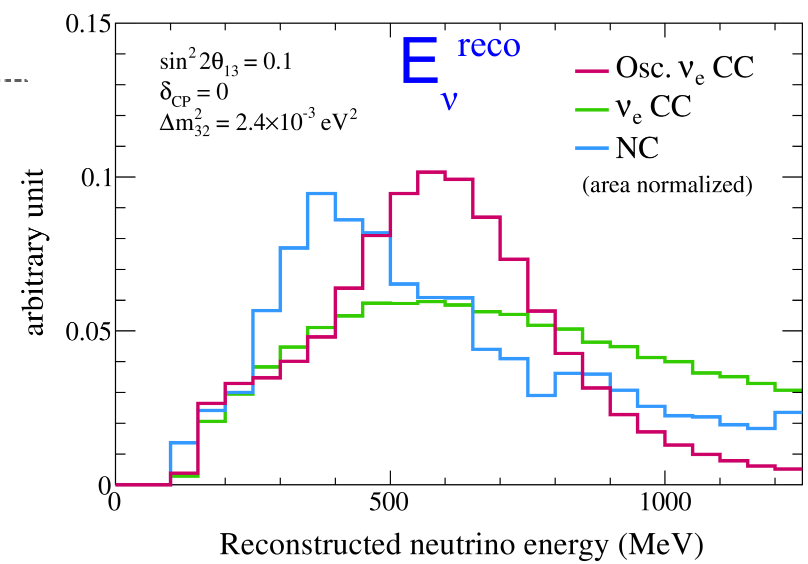
$f=(b,x)$ parameters propagated to SK fit (marginalized)

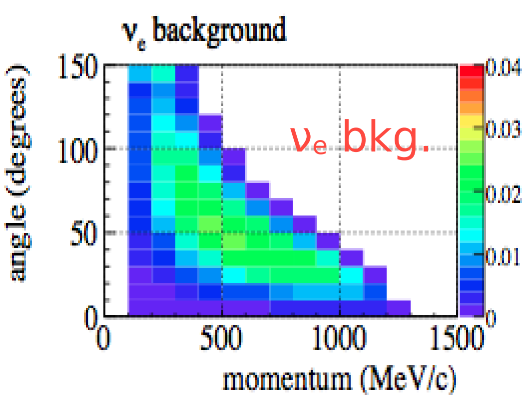
$$E^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$

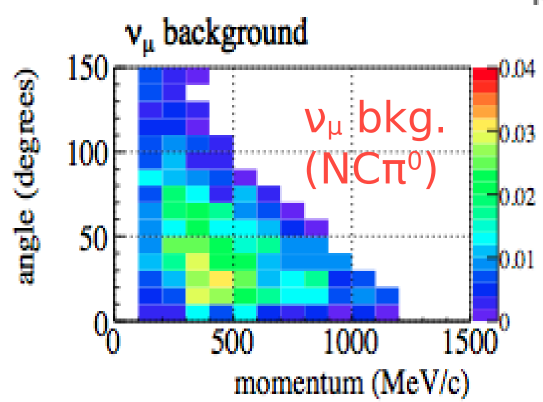


(p_e,θ_e)



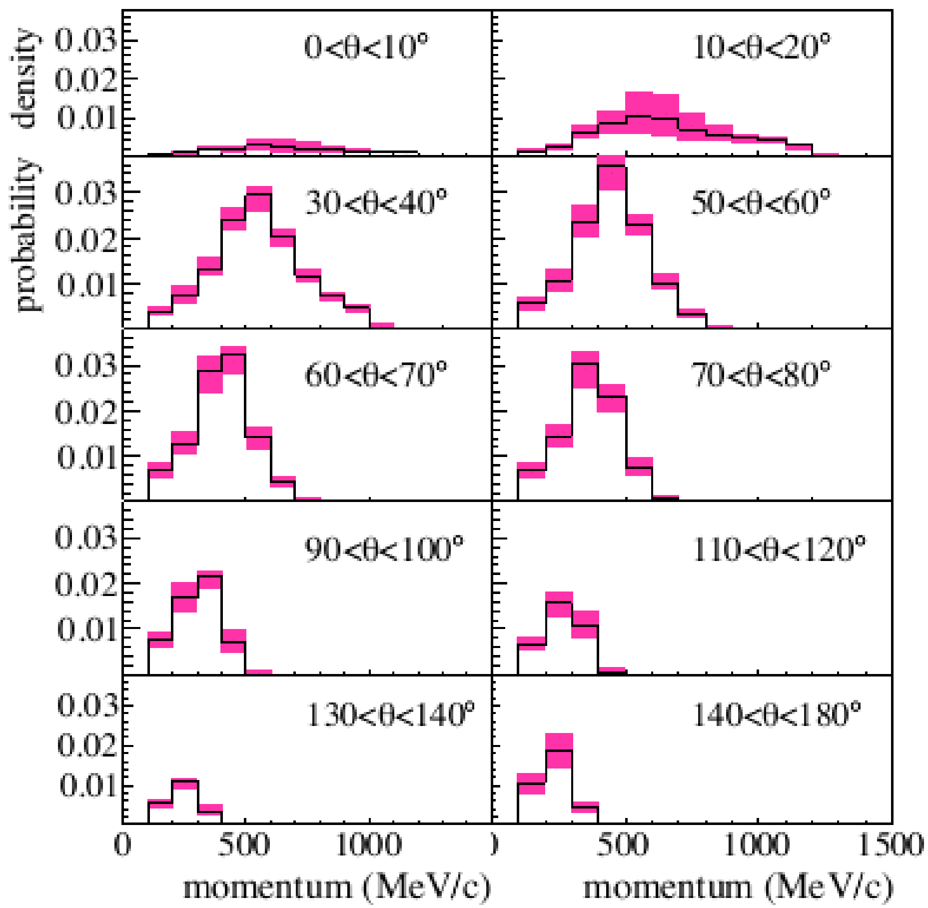




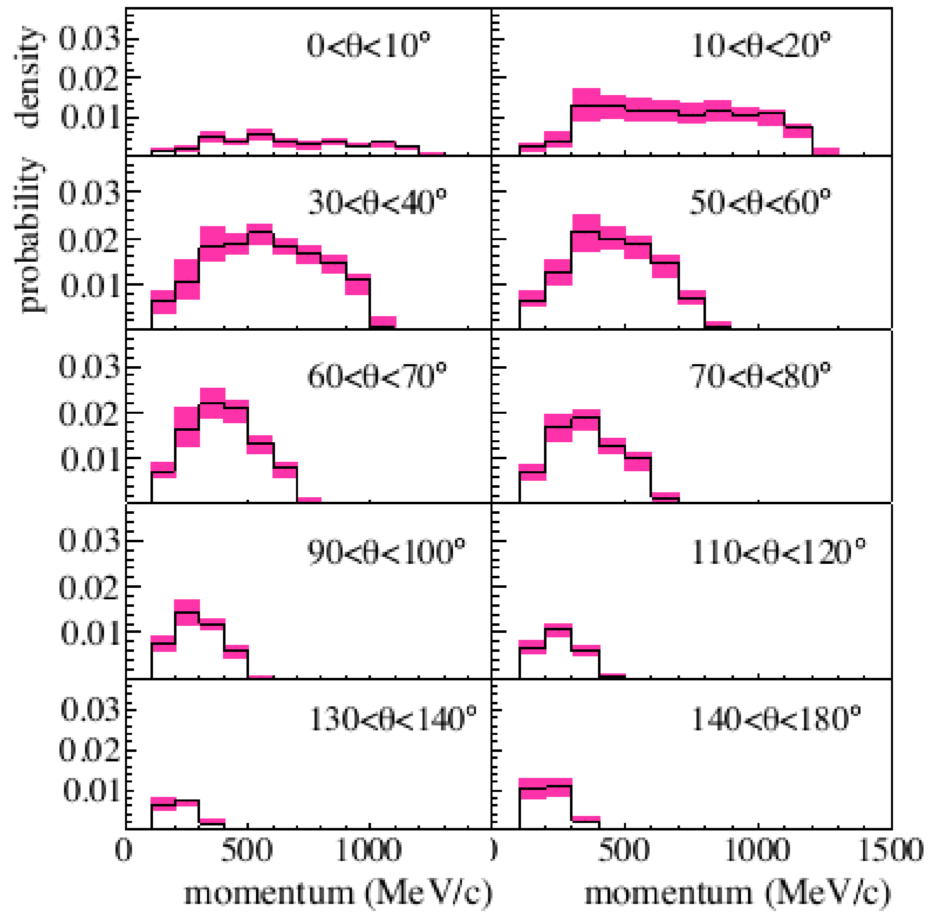


Predicted (p_e,θ_e) shape (PDF) in SK

$\sin^2 2\theta_{13} = 0.1$



$\sin^2 2\theta_{13} = 0$



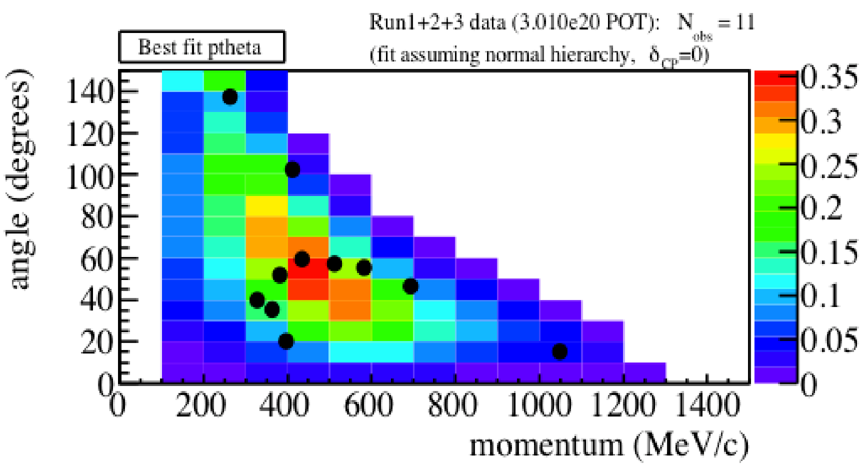
Systematic uncertainty is dominated by flux, CCQE and CC1π paraeters, x_{SF}, and SK detector efficiency

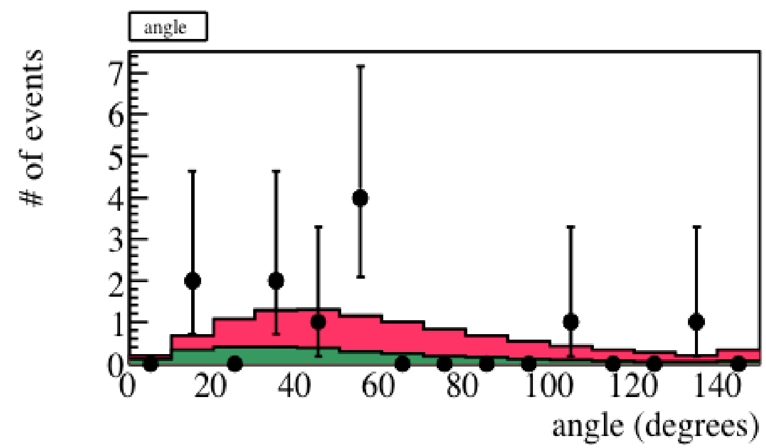
Systematic uncertainty is dominated by SK detector efficiency and W_{eff}

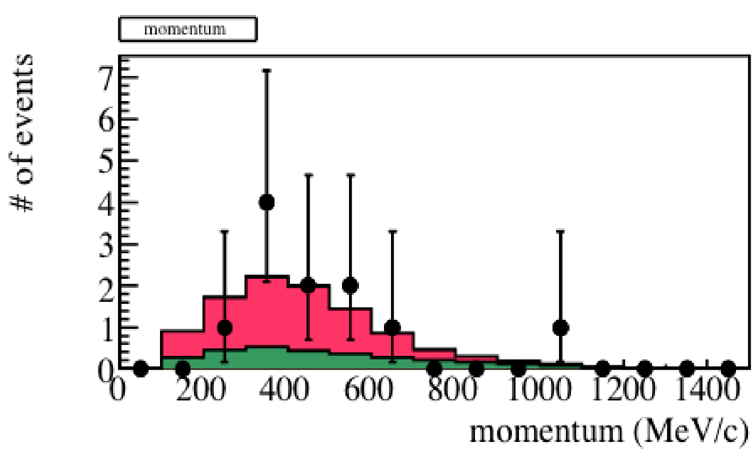
ν_e appearance fit result

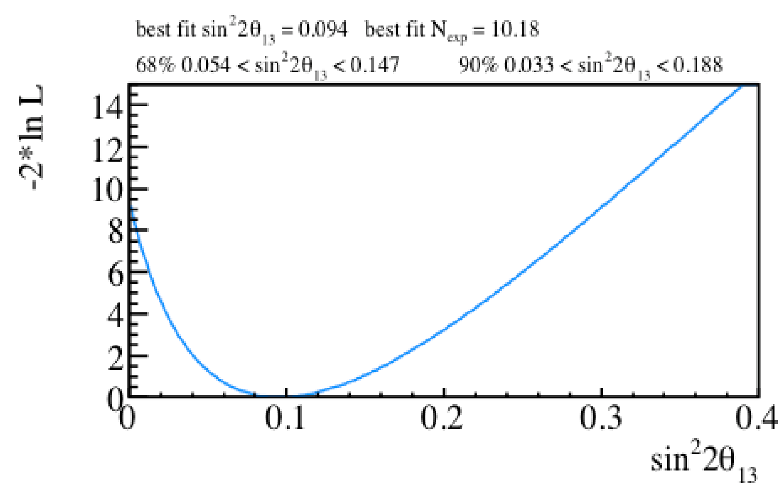
Data vs prediction at best fit point

assuming δ_{CP}=0, normal hierarchy
$|\Delta m^2_{32}|=2.4\times10^{-3}\ eV^2$, $\sin^2 2\theta_{23}=1$







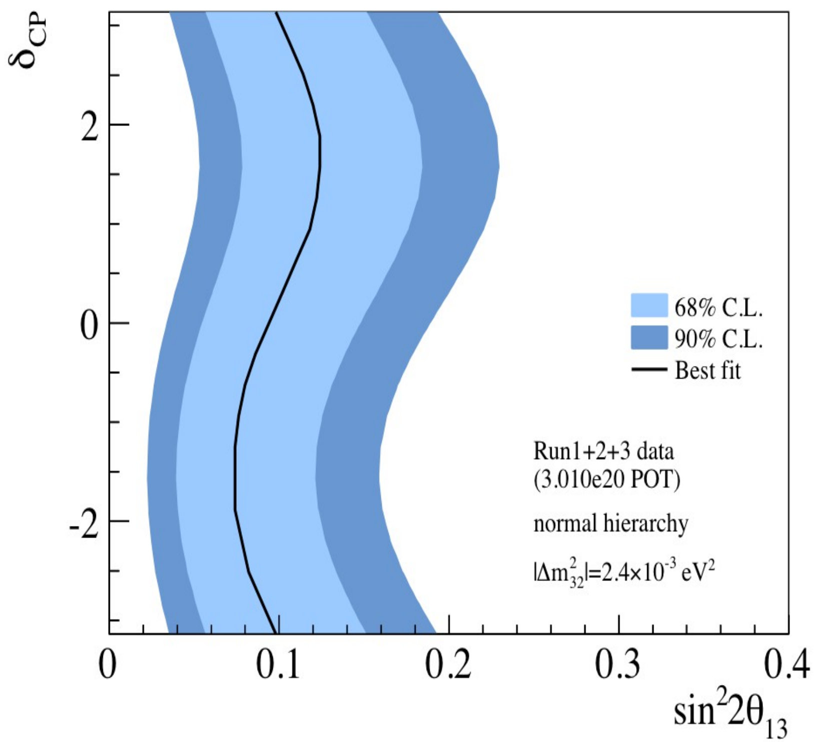


Confidence intervals

- Allowed region of $sin^2 2\theta_{13}$ (scanned over δ)

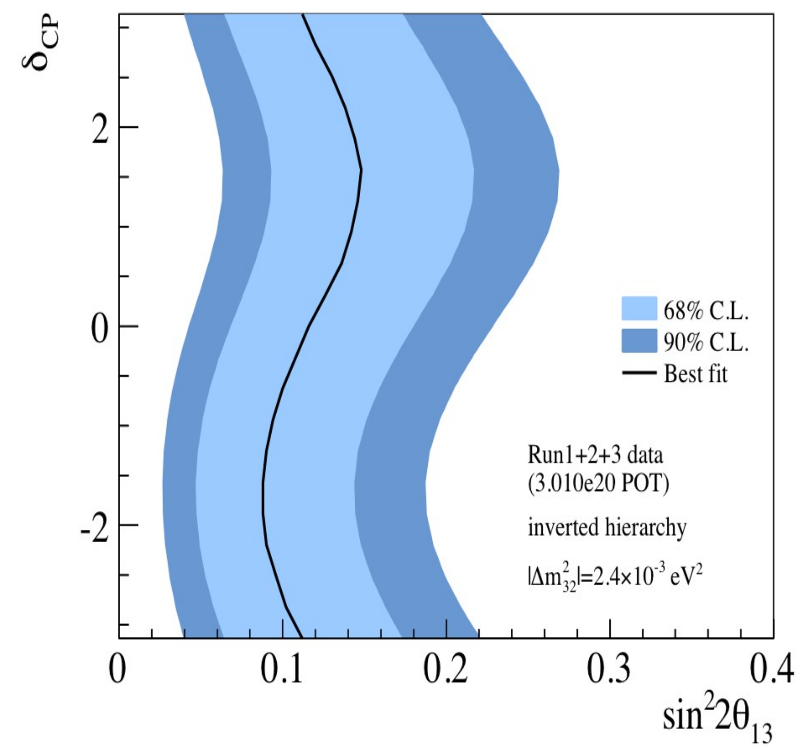
Fixed oscillation parameters:
$\Delta m^2_{12} = 7.6\times10^{-5}$ eV^2
$\Delta m^2_{32} = \pm2.4\times10^{-3}$ eV^2
$\sin^2 2\theta_{12} = 0.8704$
$\sin^2 2\theta_{23} = 1.0$
δ_{CP} is scanned

Normal hierarchy



$$\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040}$$

Inverted hierarchy



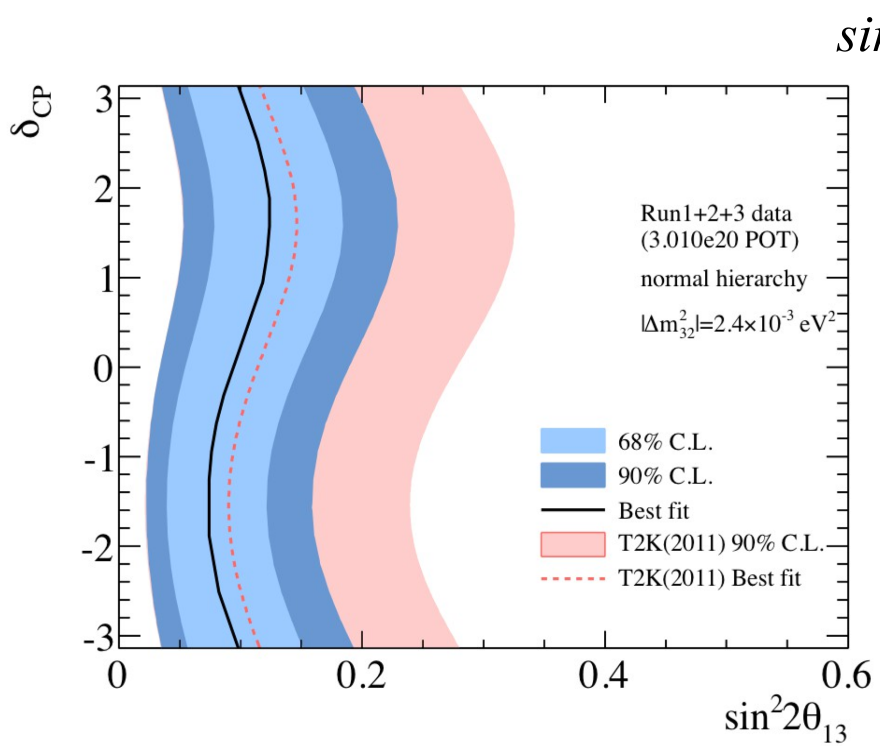
$$\sin^2 2\theta_{13} = 0.116^{+0.063}_{-0.049}$$

68% CL at δ=0

The other 2 methods give consistent results

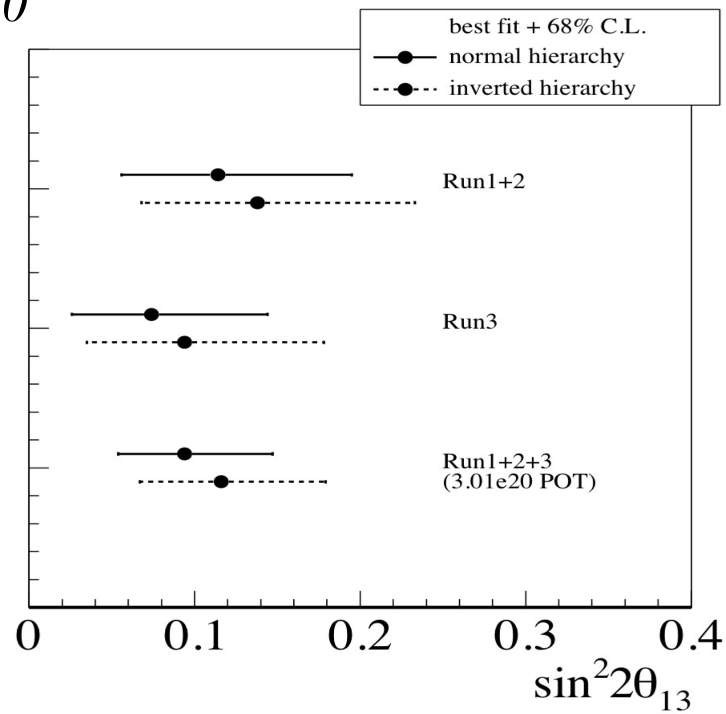
Comparison with 2011 results

Allowed region (normal hierarchy)



New, improved result is consistent with 2011 result

Best fit + 68% CL errors (δ=0)



Run 3 results is consistent with Run 1+2

ν_μ disappearance analysis

Fit the reconstructed E_ν energy in 3-flavor mixing framework

Two methods:

- extended maximum likelihood fit to rate + shape (E_ν^{reco})

vacuum oscillation
(no matter effect)

$$\mathcal{L}(\vec{o},\vec{f}) = \underbrace{\mathcal{L}_{\text{norm}}(\vec{o},\vec{f})}_{\text{expected number of events}} \times \underbrace{\mathcal{L}_{\text{shape}}(\vec{o},\vec{f})}_{\text{unbinned spectrum shape}} \times \underbrace{\mathcal{L}_{\text{syst}}(\vec{f})}_{\text{systematic uncertainties}}$$

- binned likelihood ratio (E_ν^{reco}):

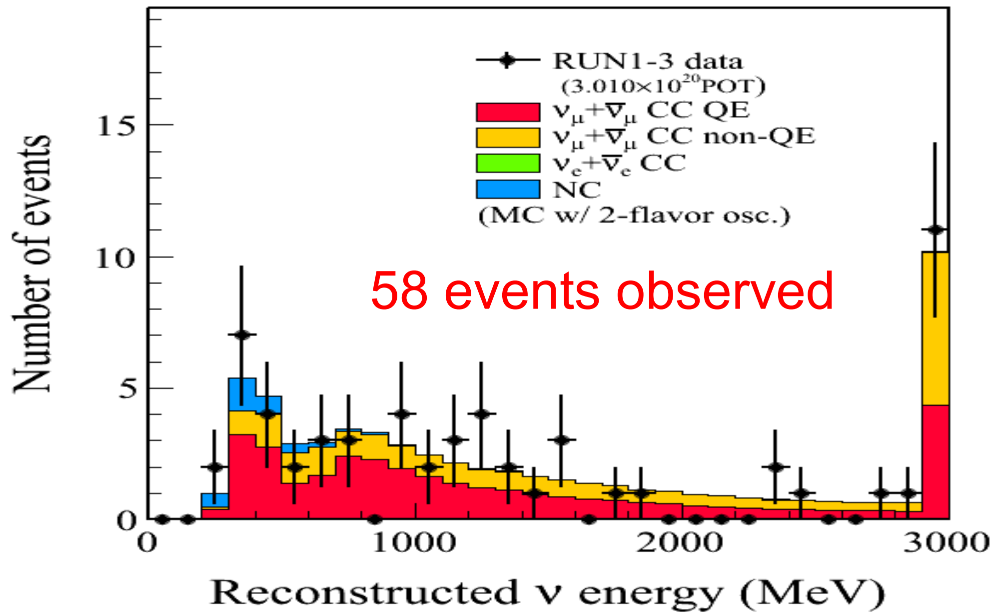
matter effect included

$$\chi^2 = \underbrace{2\sum_{E_r}\left(N_{\text{SK}}^{\text{data}} \ln \frac{N_{\text{SK}}^{\text{data}}}{N_{\text{SK}}^{\text{exp}}} + (N_{\text{SK}}^{\text{exp}} - N_{\text{SK}}^{\text{data}})\right)}_{\text{spectral distribution}} + \underbrace{(\mathbf{a}-\mathbf{a_0})^T \mathbf{C}^{-1} (\mathbf{a}-\mathbf{a_0})}_{\text{systematic parameters and correlations}}$$

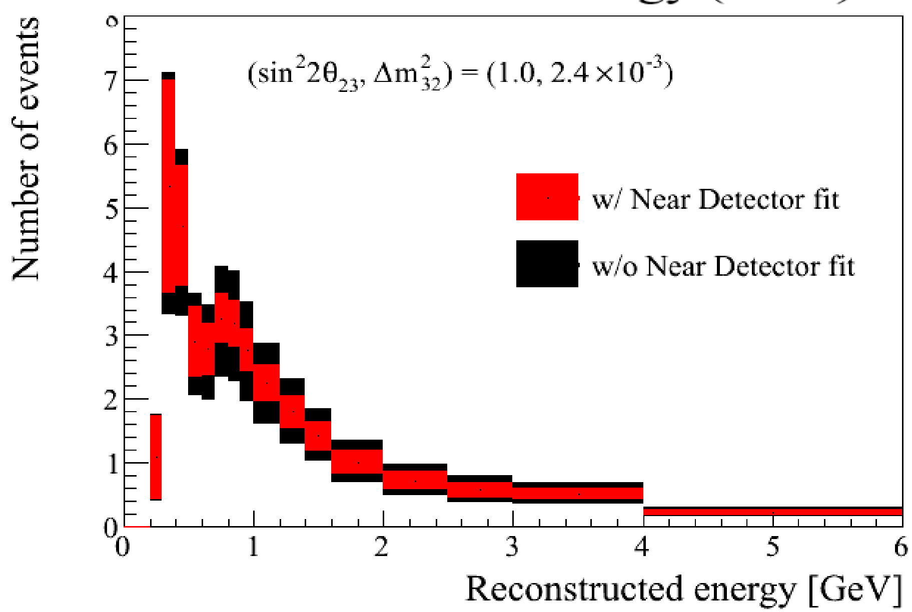
Parameter	Value
Δm^2_{21}	7.5×10^{-5} eV^2
$\sin^2 2\theta_{12}$	0.857
$\sin^2 2\theta_{13}$	0.098
δ_{CP}	0
Mass hierarchy	Normal
Baseline	295 km

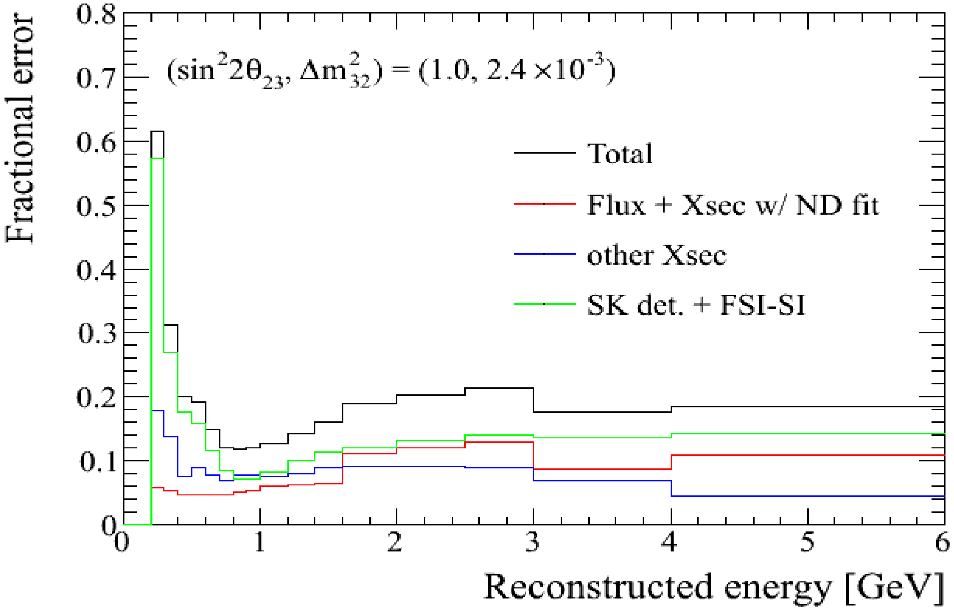
non-atmospheric oscillation parameters are fixed

ν_μ data and MC prediction

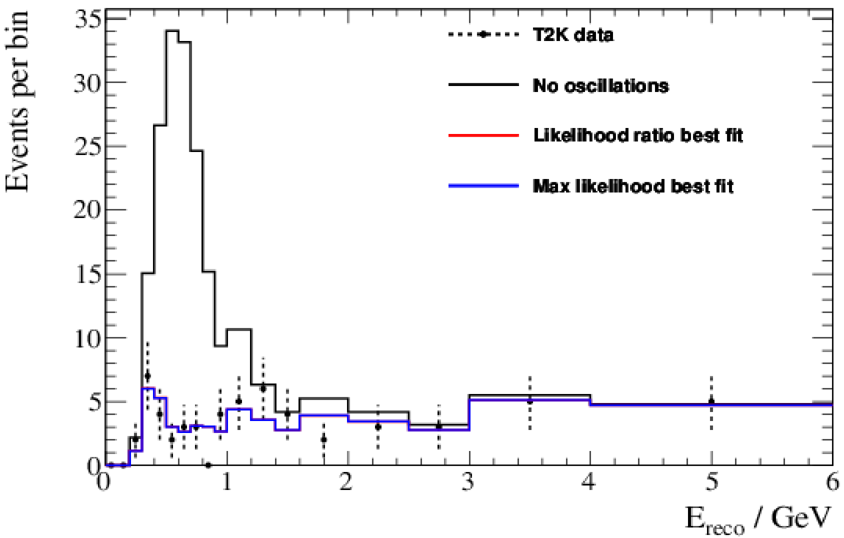


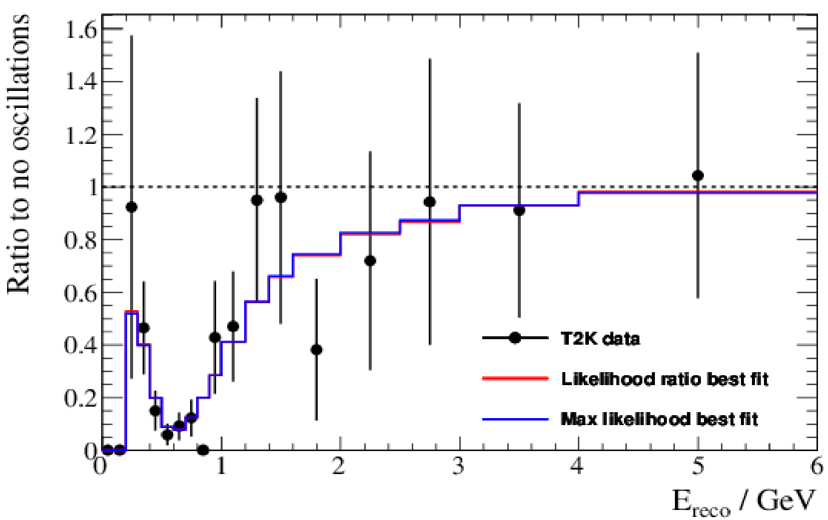
Systematic uncertainty	before ND280 fit	after ND280 fit
flux and ν x-sections	21.8	4.2
uncorrelated ν x-sections	6.3	
SK detector	10.1	
FSI-SI	3.5	
Total	**25.1**	**13.0**

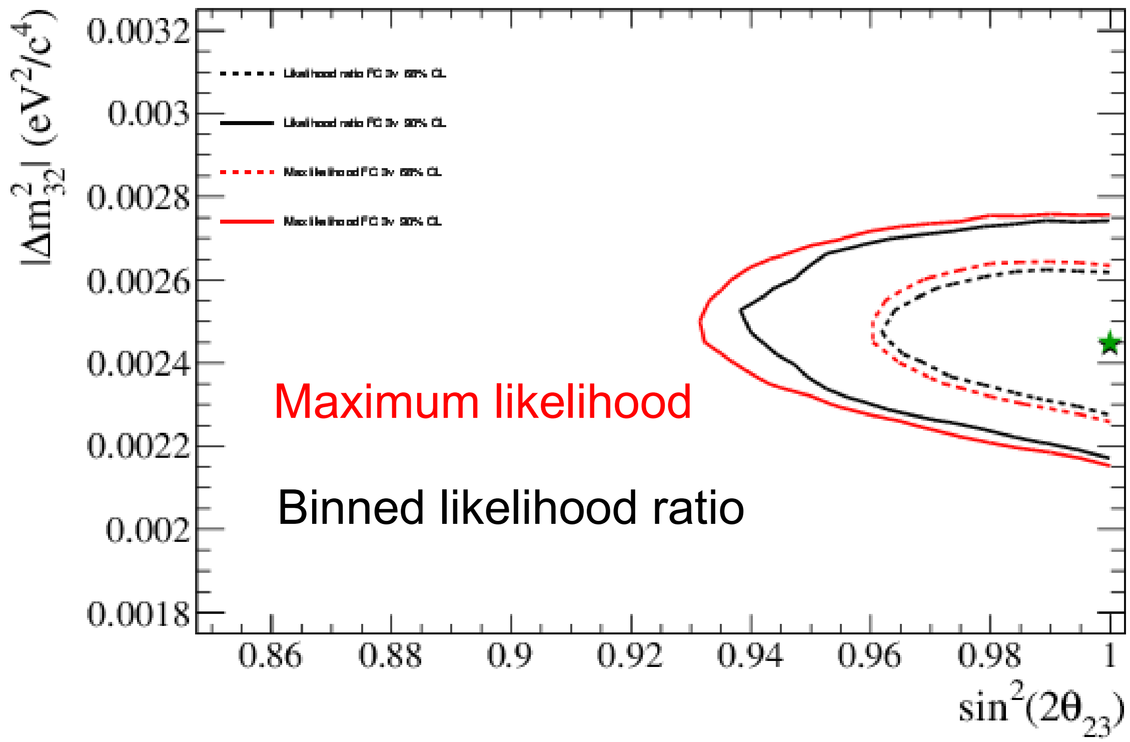




ν_μ disappearance fit





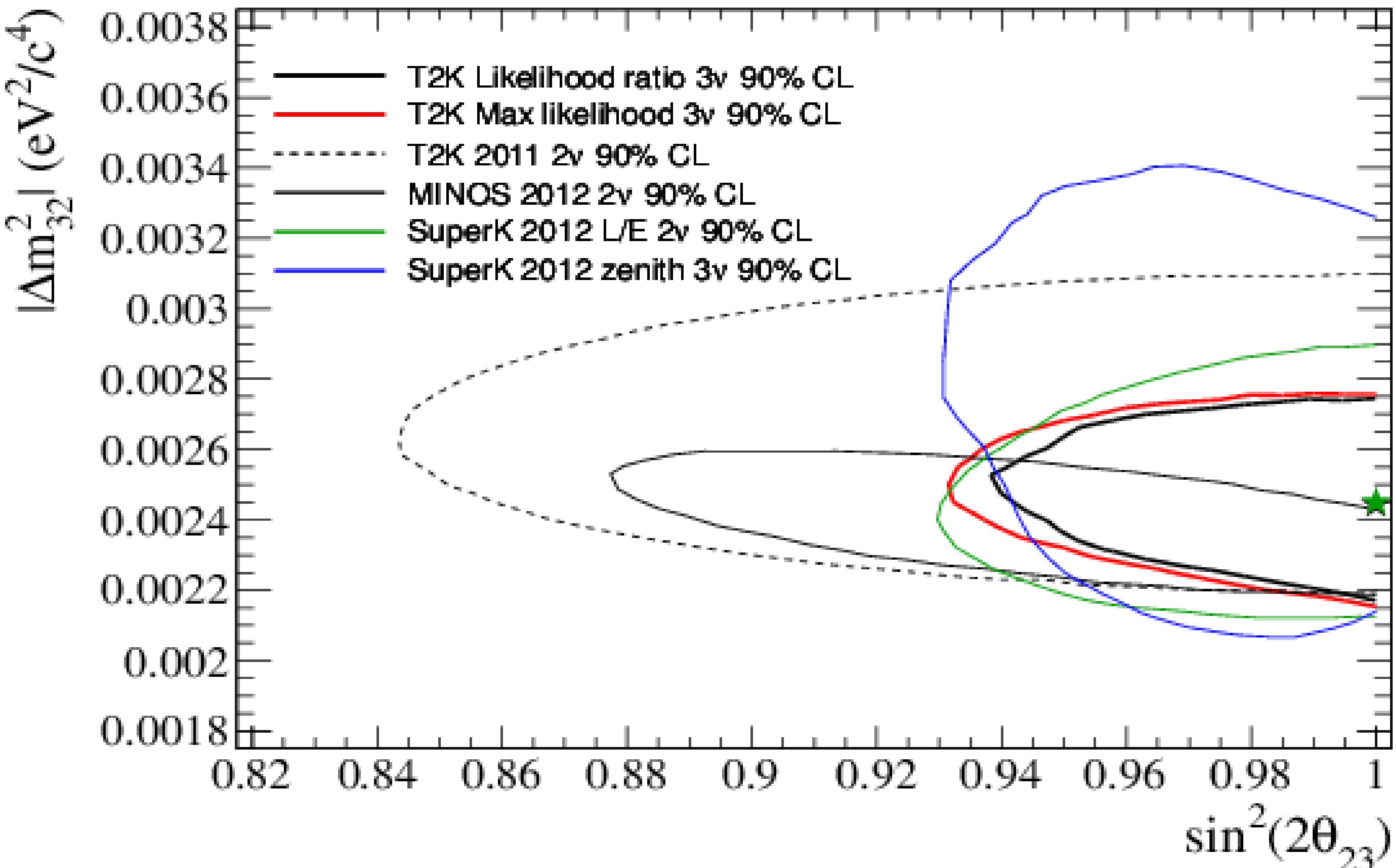


Best fit point:

Δm^2_{32} = 2.45 (2.44) x 10^{-3} eV^2

$\sin^2 2\theta_{23}$ = 1.00

Comparison to other experiments



T2K already has the best measurement of θ_{23}!

Future prospects

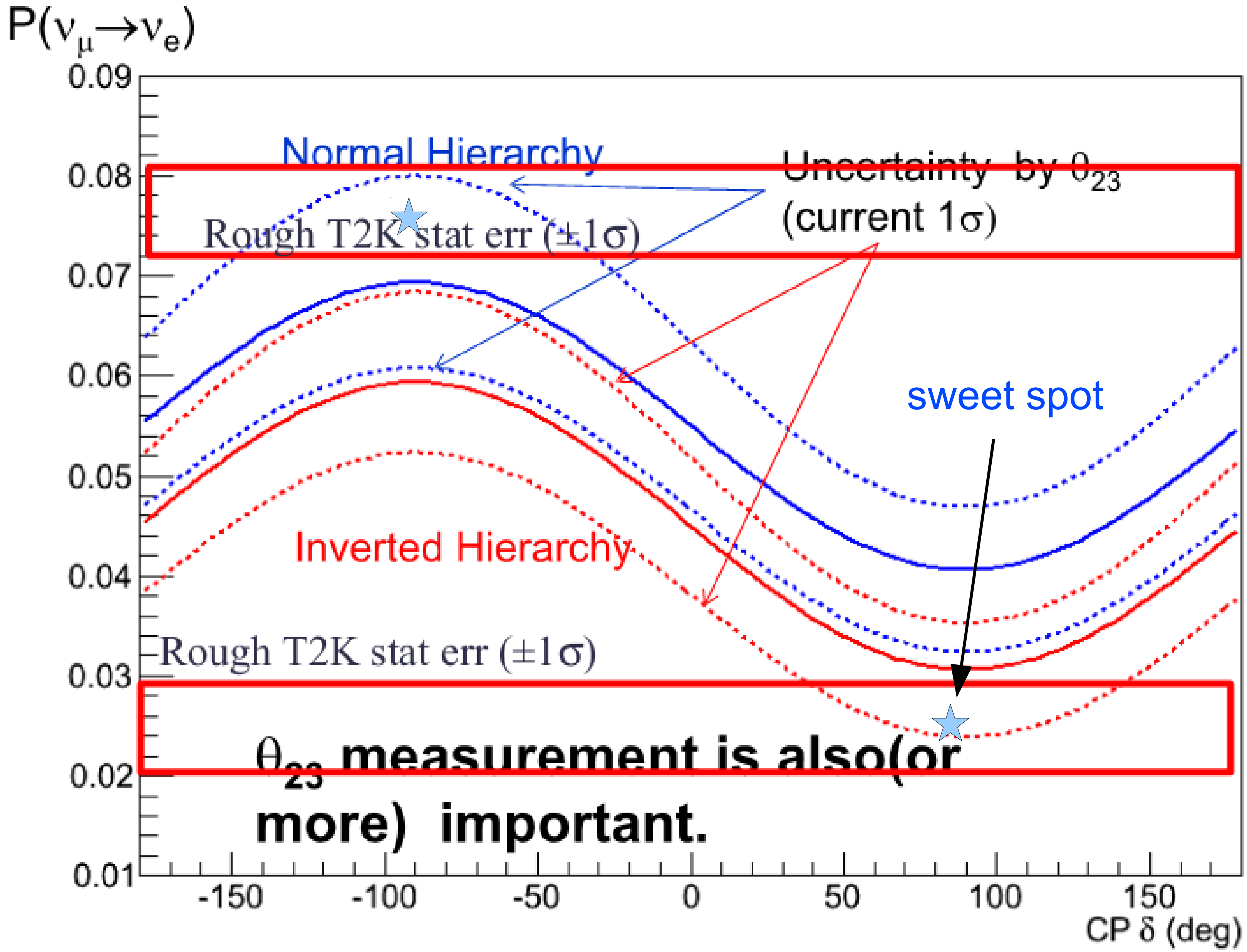
- Data taking this year is going well
  - stable running at 230 kW beam power
  - goal to reach 8×10^{20} P0T before August shutdown (~6×10^{20} now)
  - 5σ ν_e appearance signal
- 2014: 1.2×10^{21} P0T → 2015: 1.8×10^{21} P0T → ultimately: 7.8×10^{21} P0T
- Improve measurement of appearance probability: combined with reactor results to see first hint of CPV and mass hierarchy
- Precise measurement of θ_{23}: maximal or not; also important for CPV measurement
- Explore the possibility of anti-neutrino running

Conclusion

- T2K has restarted data taking last year after the 2011 earth quake and
- Latest oscillation result based on first 3 years of data (4% of total):
  - observed 11 ν_e candidate (3.2 background): 3.2σ observation
  - observed 58 ν_μ candidates: best measurement of $\sin^2 2\theta_{23}$
- Nature has been kind to provide a reasonably large θ_{13}
  - opens the way to explore CP violation in T2K, Nova, LBNE

Extra slides

Probing CPV and mass hierarchy



θ_{23} measurement is also(or more) important.

Accelerator upgrade

- Beam loss at MR injection limits proton/bunch ~ $3\text{x}10^{13}$ ($1.5\text{x}10^{13}$ now, $4.1\text{x}10^{13}$ design)
- Path to 750 kW beam power (~2017)
  - x2 proton/bunch
    - LINAC upgrade (2013): ion source, RFQ (30 mA to 50 mA)
    - RCS 400 MeV injection
    - Capable to operate RCS upto 1MW (300 kW now)
    - MR RF higher harmonics
  - x2 higher rep rate (spill period from 2.5 s to 1.3 s)
    - Replace all MR magnet power supplies (~5 years)
    - High gradient RF core

MR beam power = [RCS power] x (30GeV/3GeV) x {8bnch/(2x25HzxTMR)}
= 0.64 x [RCS power] @ MR 2.48s cycle Now
= 1.25 x [RCS power] @ MR 1.28s cycle

Appearance probability

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \ (1 - 2S_{13}^2)\right)$$

θ_{13}

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

CPC

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

CPV

$$+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

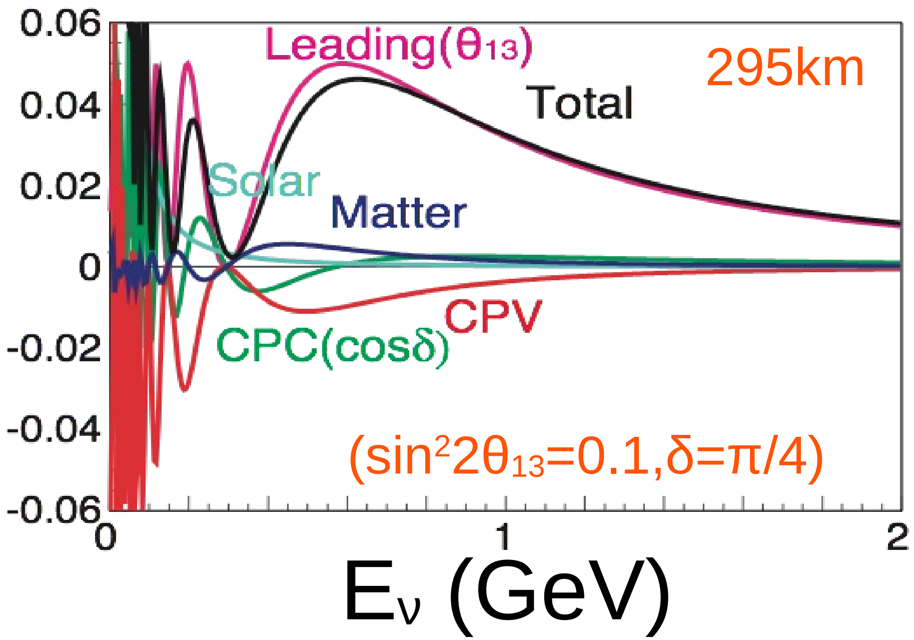
Solar

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \ (1 - 2S_{13}^2)$$

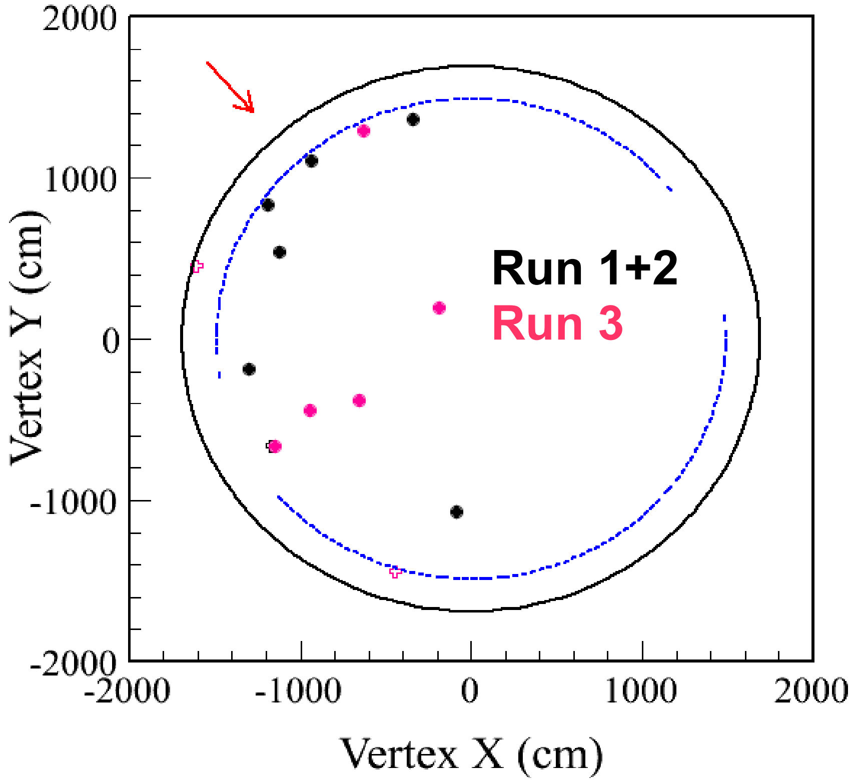
Matter effect (small in T2K)

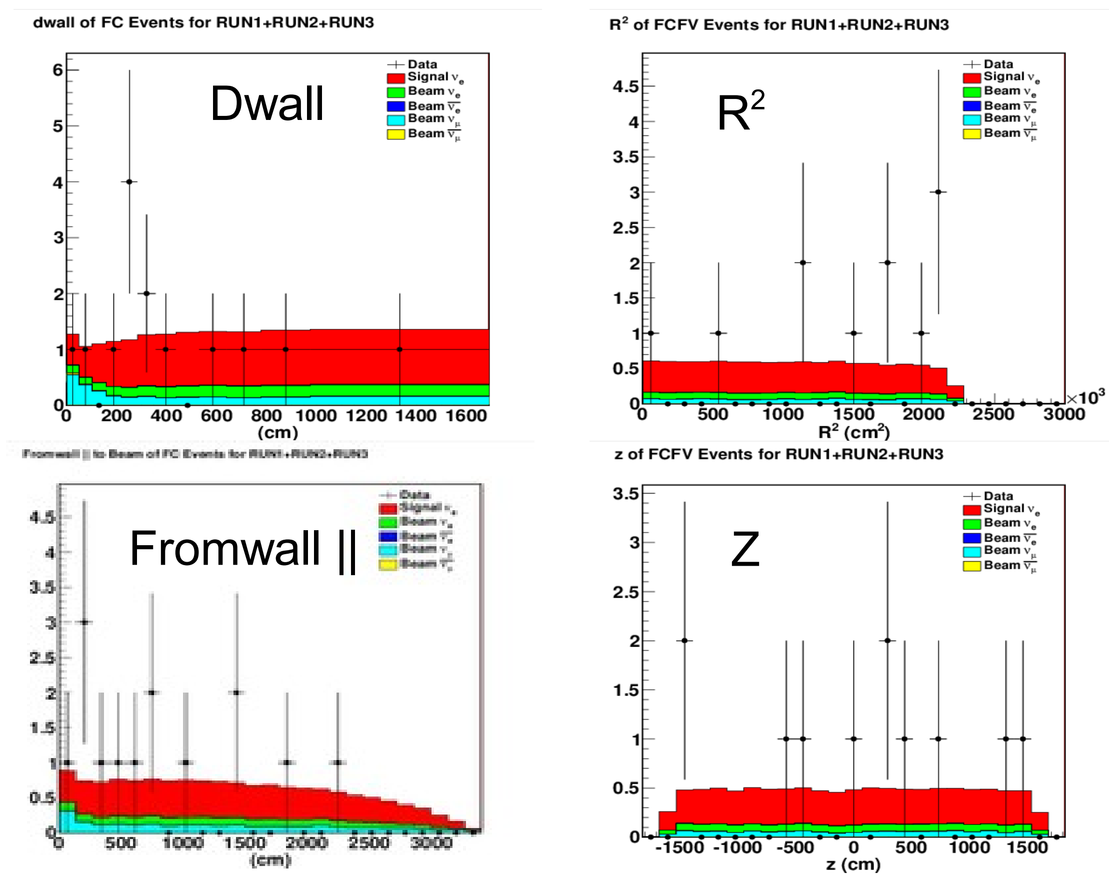
- $a \rightarrow -a$ and $\delta \rightarrow -\delta$ for $\nu_\mu \rightarrow \nu_e$

$$a = 7.56\times10^{-5}[\mathrm{eV}^2]\cdot\left(\frac{\rho}{[\mathrm{g/cm^3}]}\right)\cdot\left(\frac{E}{[\mathrm{GeV}]}\right)$$



ν_e candidate vertex distribution





	RUN1+2	RUN3	RUN1+2+3
$Dwall$	22.9%	94.7%	39.4%
$Fromwall$ beam$_{\|\|}$	1.34%	35.2%	6.05%
$R^2 + Z$	10.5%	74.6%	32.4%

p values of different distributions evaluated with toy MC

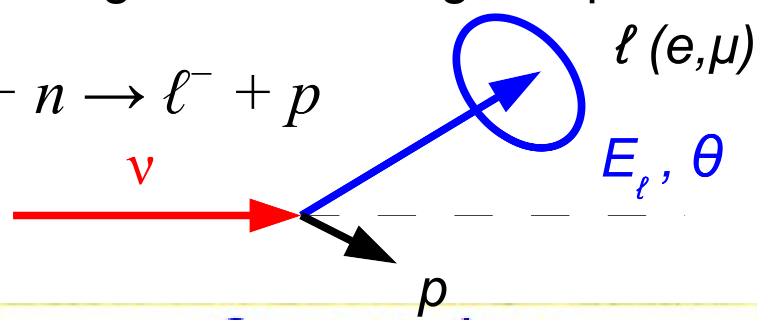
E_ν measurement

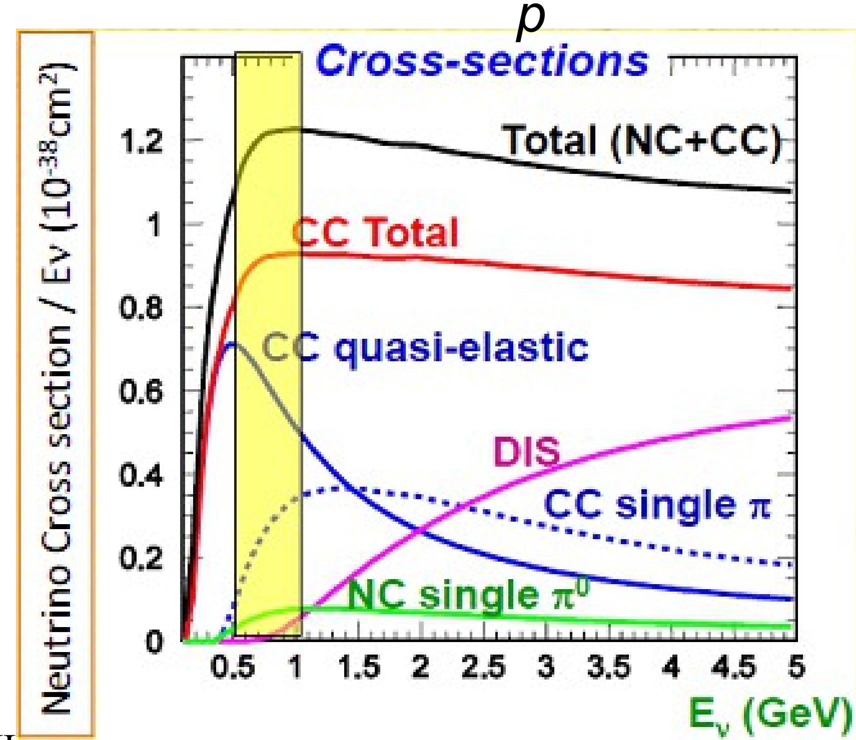
Charge Current Quasi-elastic interaction dominates at the T2K energy

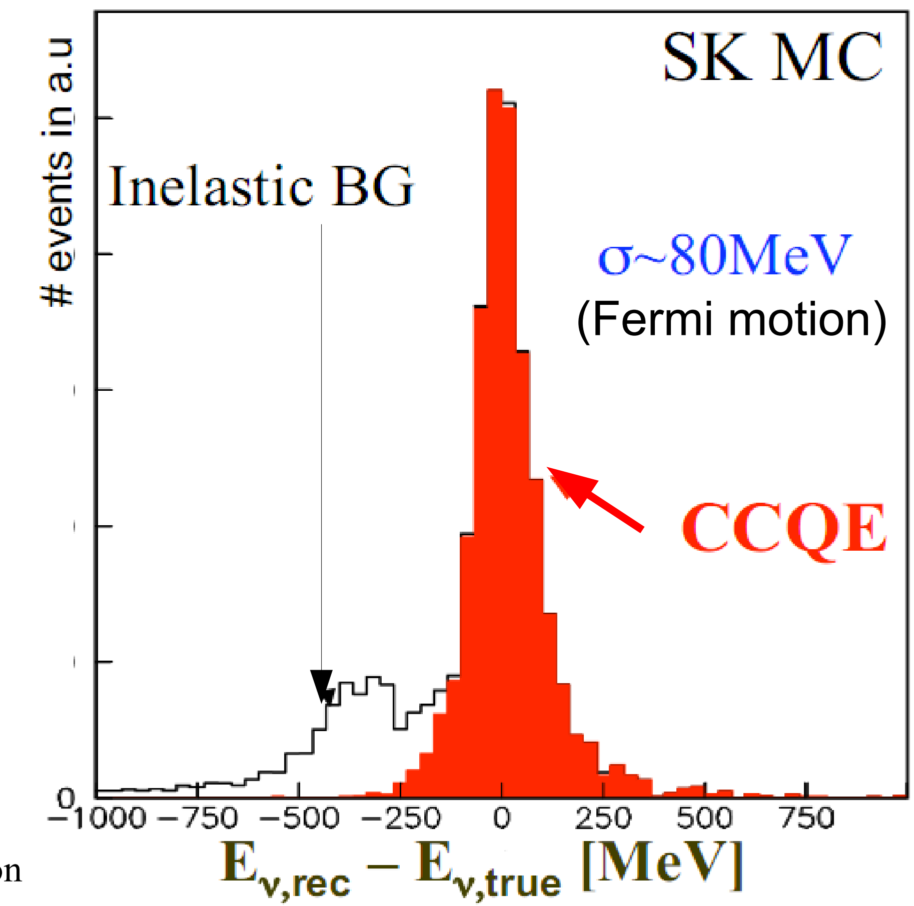
- E_ν can be reconstructed from the energy and angle of the charged lepton

$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos\theta_l}$$

$$\nu_\ell + n \rightarrow \ell^- + p$$







Piecewise fitting

Maximize the global likelihood with respect to the oscillation ($\bar{o}$), beam ($\bar{b}$), and cross section ($\bar{x}$) parameters considering all relevant (external and internal) data... Too difficult!

$$\mathcal{L}_{\rm tot}(\vec{b},\vec{x},\vec{o}) = \mathcal{L}_{\rm pbeam}(\vec{b}) \times \mathcal{L}_{\rm NA61}(\vec{b}) \times \mathcal{L}_{{\rm ext}-\nu}(\vec{x}) \times \mathcal{L}_{\rm ND280}(\vec{b},\vec{x}) \times \mathcal{L}_{\rm SK}(\vec{b},\vec{x},\vec{o})$$

Piecewise approach: the data is fitted in steps and the constraints on the nuisance parameters, $\bar{b}$ and $\bar{x}$, are propagated b/w steps taking into account their uncertainties and correlations:

- individual likelihood for flux and external cross section parameters are evaluated using external hadron production and internal beam measurements (prior ND280 and SK data)
- Fit the ND280 data using a combined likelihood that includes the prior constraints on the flux and cross section parameters
- Final fit to SK data: combine the SK data and the above constraint from the near detector into a joint likelihood

Flux and cross section parametrization

Parametrize the degrees of freedom in the flux and cross section models:

$\vec{b} = (b_1^{nd280}, b_2^{nd280}, \ldots b_1^{sk}, b_2^{sk}, \ldots)$	Normalization of the flux in true neutrino energy bins at ND280 and SK
$\vec{x} = (x_{MA}^{QE}, x_{MA}^{RES}, x_{norm}^{QE}, x^{pF} \ldots)$	Semi-empirical cross section model parameters (e.g. axial mass, fermi momentum) and energy dependent normalization parameters

Evaluate prior (to T2K neutrino data) constraints on the flux and cross section models:

$\ln L_{flux}(\vec{b}) = \frac{-1}{2} \Delta b\, V_b^{-1} \Delta b^T$	Constraint from NA61 and other hadron production data, proton beam monitors
$\ln L_{xsec}(\vec{x}) = \frac{-1}{2} \Delta x\, V_x^{-1} \Delta x^T$	Constraint from external neutrino data and pion scattering data

ND280 and SK combined likelihood

Form a binned likelihood with the ND280 inclusive muon sample and the prior constraints on the flux and cross section models

$$\ln L_{NEAR}(\vec{b},\vec{x},\vec{d}|\vec{N}_{ND280}) = \boxed{\ln L_{xsec}(\vec{x})} + \boxed{\ln L_{flux}(\vec{b})} + \boxed{\ln L_{det}(\vec{d})}$$

Uncertainties in the ND280 reconstruction

$$+\boxed{\ln L_{ND280}(\vec{b},\vec{x},\vec{d}|\vec{N}_{ND280})}$$

Binned likelihood of the ND280 inclusive muon data

Maximize the likelihood and marginalize over *d* and *x* parameters that are not propagated to the SK oscillation fits

$$\ln L_{NEAR}^{max}(\vec{b},\vec{x}) = \frac{-1}{2}\Delta\vec{f}\, V_f^{-1}\Delta\vec{f}^{T}$$

***f* = (*b*,*x*)** includes flux and cross section parameters, $\boldsymbol{V_f}$ includes their correlations

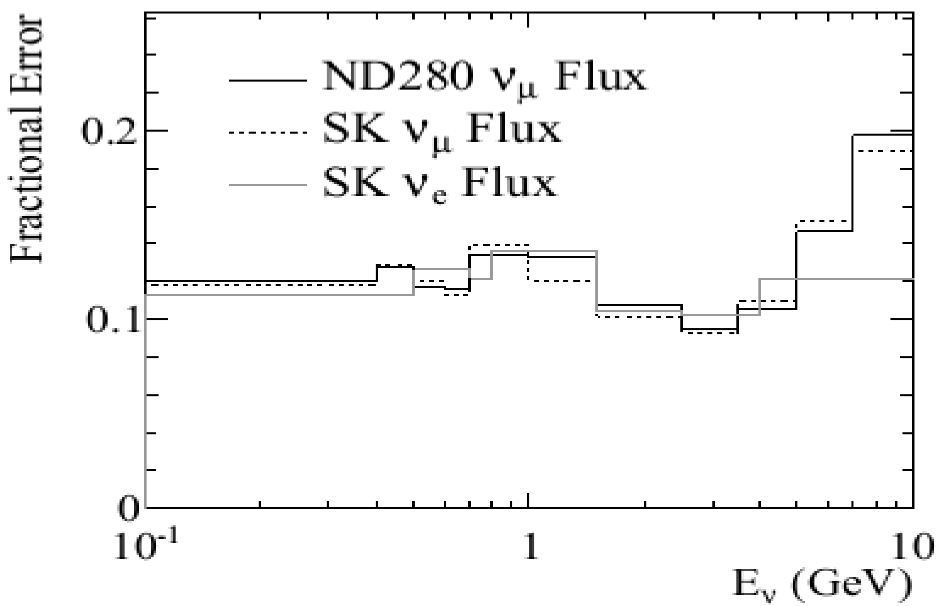
Construct the likelihoods for oscillation fits to SK data including the near detector constraint

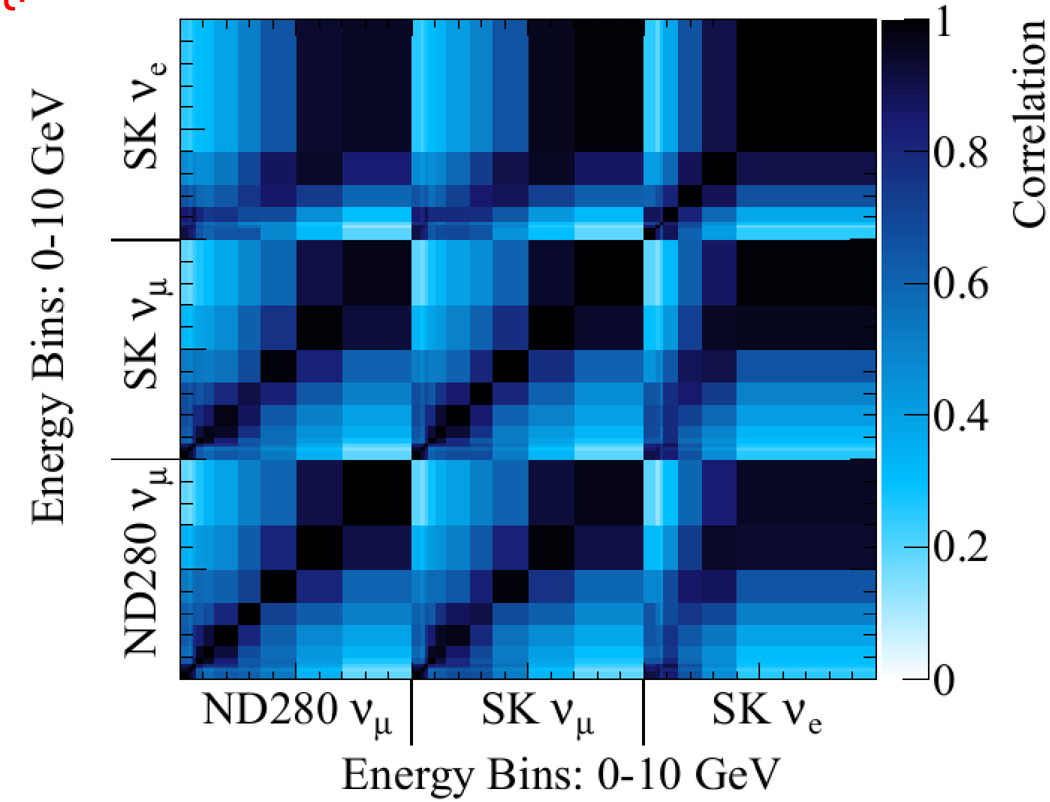
$$\ln L_{total}(\vec{o},\vec{f},\ldots|\vec{N}_{SK}) = \ln L_{NEAR}^{max}(\vec{f}) + \ln L_{SK}(\vec{o},\vec{f},\ldots|\vec{N}_{SK})$$

Flux covariance matrix

The flux parameters scale the flux in bins of nu
energy and flavor at each detector

- ν_μ: 0.0, 0.4, 0.5, 0.6, 0.7, 1.0, 1.5, 2.5, 3.5, 5.0, 7.0, 30.0 GeV
- $\bar{\nu}_\mu$: 0.0, 1.5, 30.0 GeV
- ν_e: 0.0, 0.5, 0.7, 0.8, 1.5, 2.5, 4.0, 30.0 GeV
- $\bar{\nu}_e$: 0.0, 2.5, 30.0 GeV





- Covariance evaluated between the flux parameters, built from beam and external hadron production data

Flux covariance calculation

- The effect of uncertainties (nuisance parameters) related to hadron production model, proton beam profile, horn currents are evaluated on the predicted flux by calculating the fractional covariance matrix (in nu energy and flavor, and detector bins)

Hadron interaction and proton beam profile uncertainties (described by several correlated parameters), the parameters are sampled according to their covariance and then the fractional (flux) covariance is calculated from a large sample of reweighted fluxes:

$$v_{ij} = \frac{1}{N}\sum_{k=1}^{N}\frac{(\phi_i^{nom}-\phi_i^k)(\phi_j^{nom}-\phi_i^k)}{\phi_i^{nom}\phi_j^{nom}}.$$

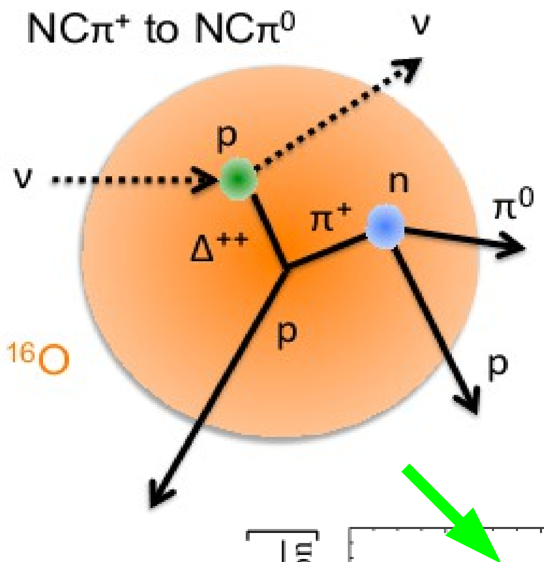
Horn and target alignment and horn current and field uncertainties, that cannot be treated by reweighting, the flux is calculated at ±1σ variation of the parameter and the fractional covariance is calculated as

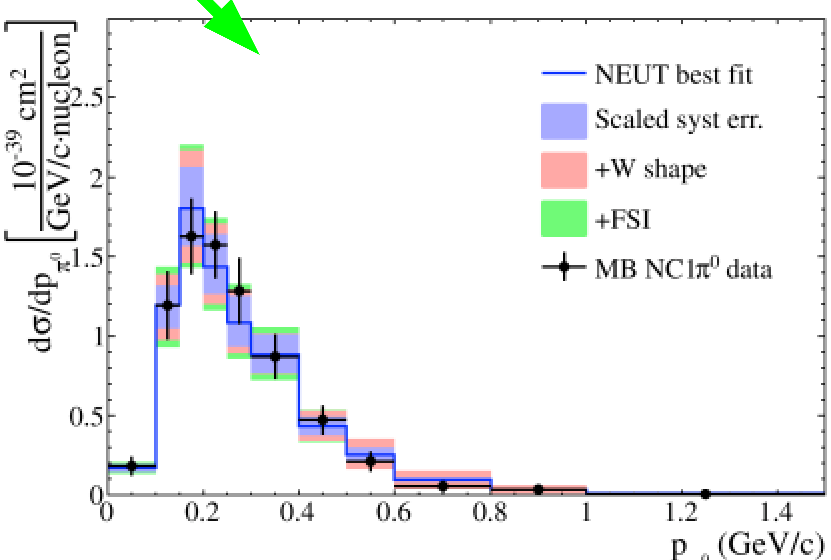
$$v_{ij} = \frac{1}{2}\frac{(\phi_i^{nom}-\phi_i^+)(\phi_j^{nom}-\phi_i^+)}{\phi_i^{nom}\phi_j^{nom}} + \frac{1}{2}\frac{(\phi_i^{nom}-\phi_i^-)(\phi_j^{nom}-\phi_i^-)}{\phi_i^{nom}\phi_j^{nom}}.$$

- The total fractional flux covariance (Vb) is the sum of the fractional covariance matrices calculated for each uncertainty source.
- In the fits to the near and far detector data, the variation of the flux prediction is modeled by parameters (b) that scale the flux in bins of nu energy, flavor and detector. The covariance matrix of the b parameters is the total fractional covariance matrix.

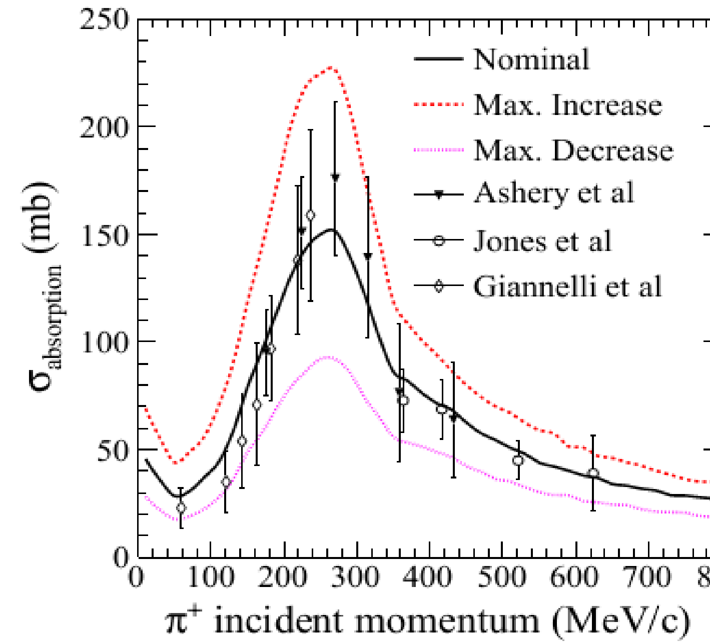
FSI tuning

NEUT FSI cascade model: pion absorption, charge exchange, elastic scattering





Result of tuning (and error envelope) to macroscopic pion absorption data:



FSI covariance matrix is combined with detector systematics

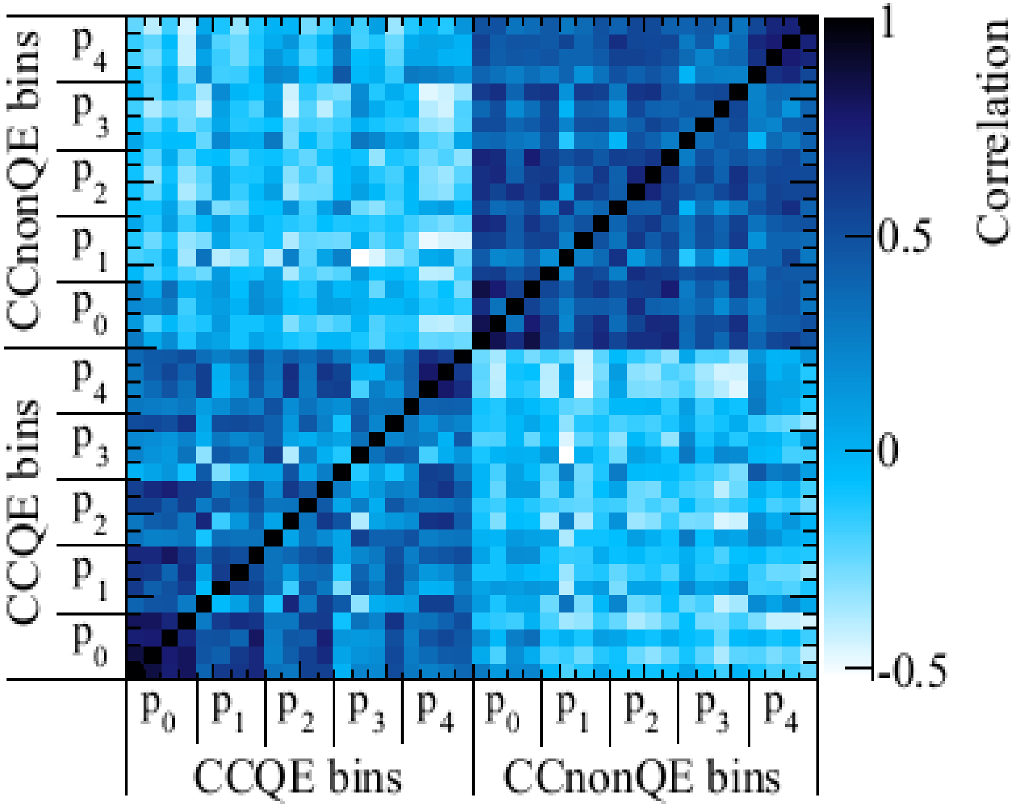
ND280 detector systematics

- Uncertainties on the selection efficiency, momentum reconstruction, migration between samples
- evaluated with beam data, cosmic and simulated events

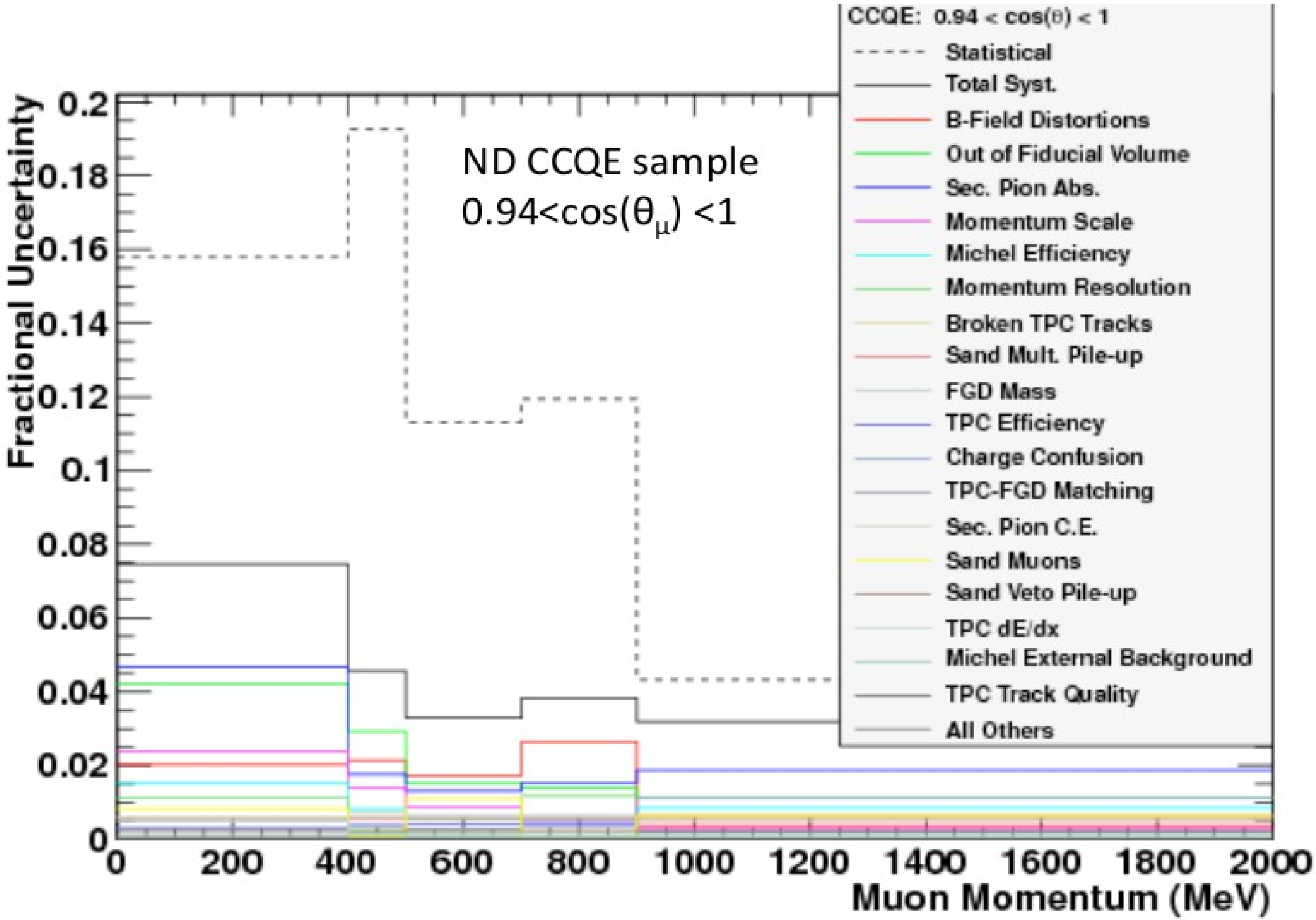
Systematic error	Error Size (%)	
	Minimum and maximum fractional error	Total fractional error
B-Field Distortions	0.3 - 6.9	0.3
Momentum Scale	0.1 - 2.1	0.1
Out of FV	0 - 8.9	1.6
Pion Interactions	0.5 - 4.7	0.5
All Others	1.2 - 3.4	0.4
Total	2.1 - 9.7	2.5

- Total covariance matrix: representing the fractional uncertainty on the predicted event number in each observable bin
- plus other efects

$$V_d = V_{det} + V_{FSI} + V_{Wshape} + V_{CCCOH} + V_{NCOTH}$$



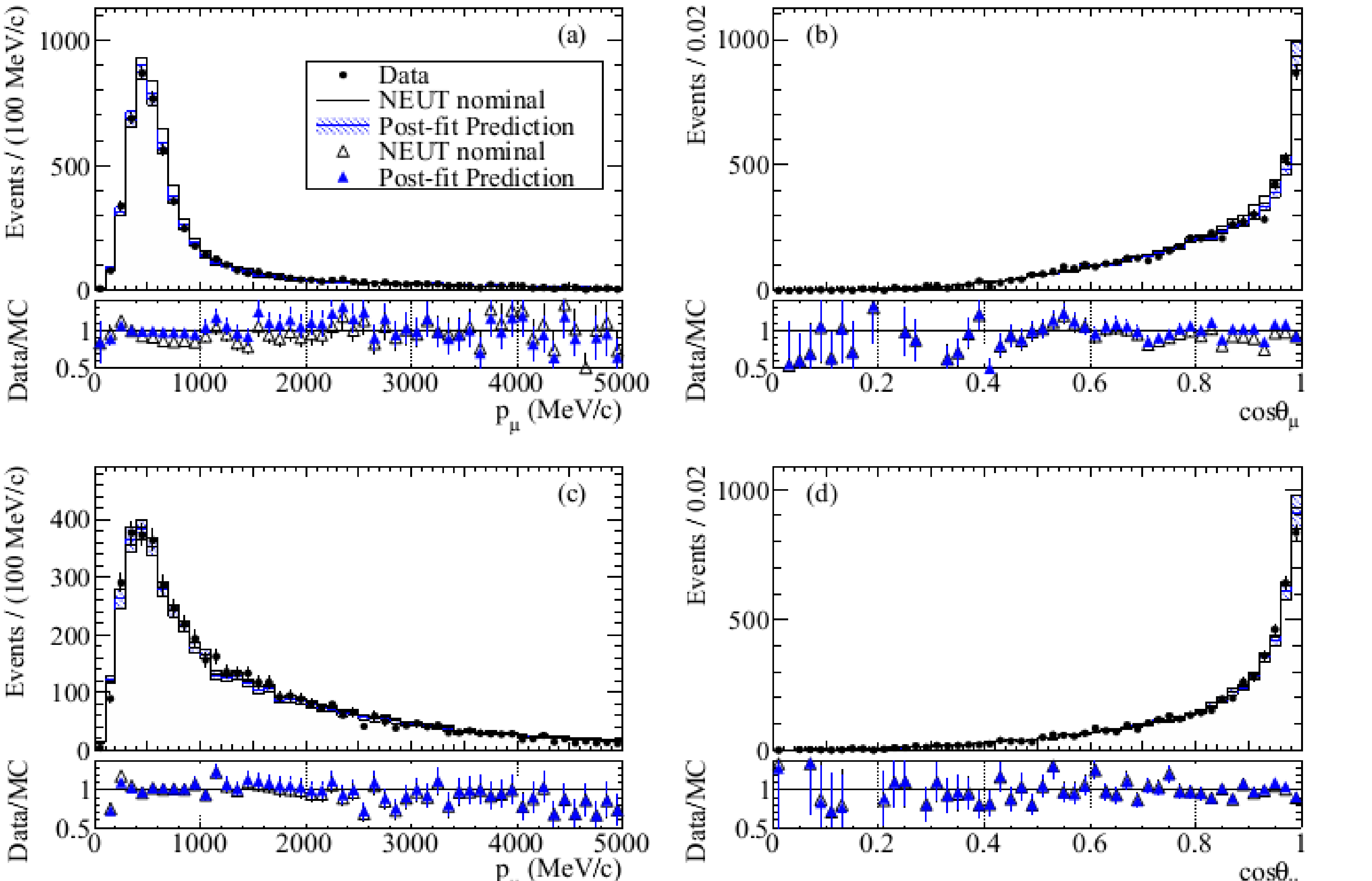
ND280 detector systematics



- Based special control samples (sand muon, cosmic, etc.)
- Currently, statics dominates

ND280 ν_μ CC consistency check

- data and MC comparison before/after fit with fine binning



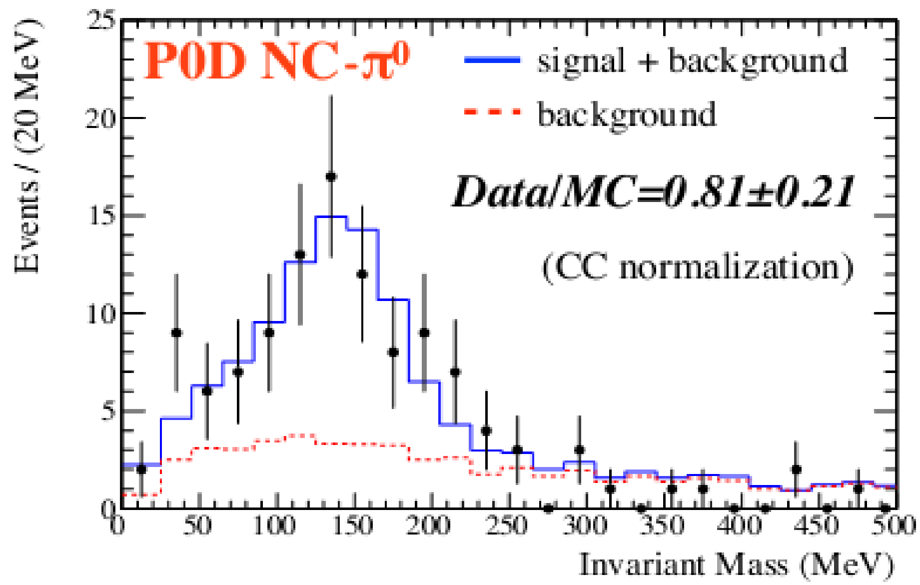
ND280 consistency check

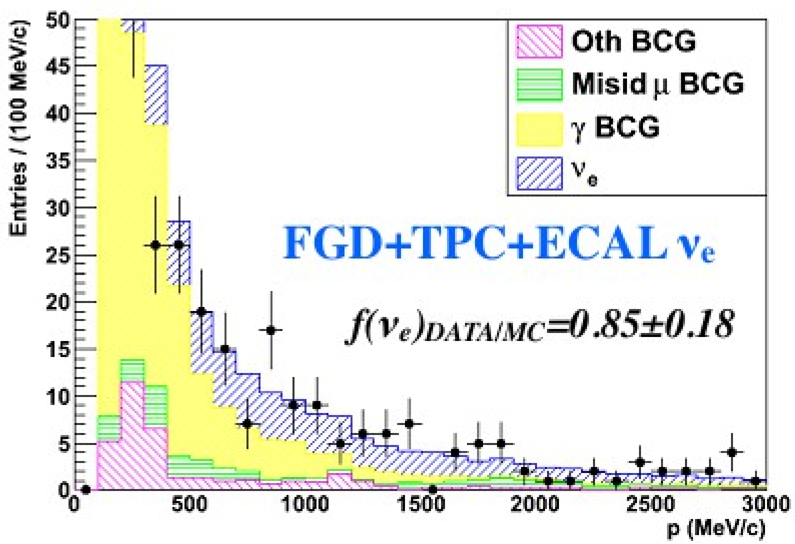
PRELIMINARY

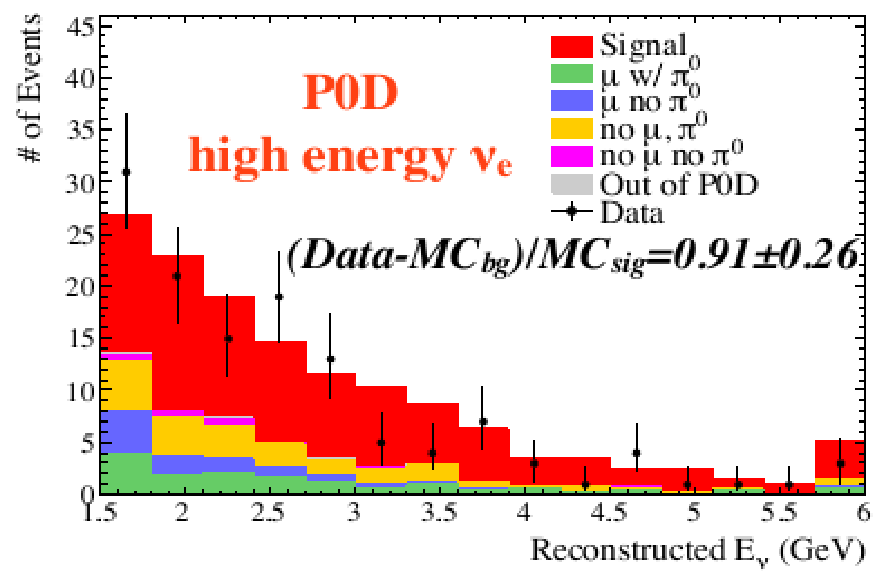
Intrinsic ν_e beam component and NC π^0 rate in the near detector

- represent the main background sources to ν_e appearance
- not yet included in fit (b/c low stat)

MC predictions are consistent with the data







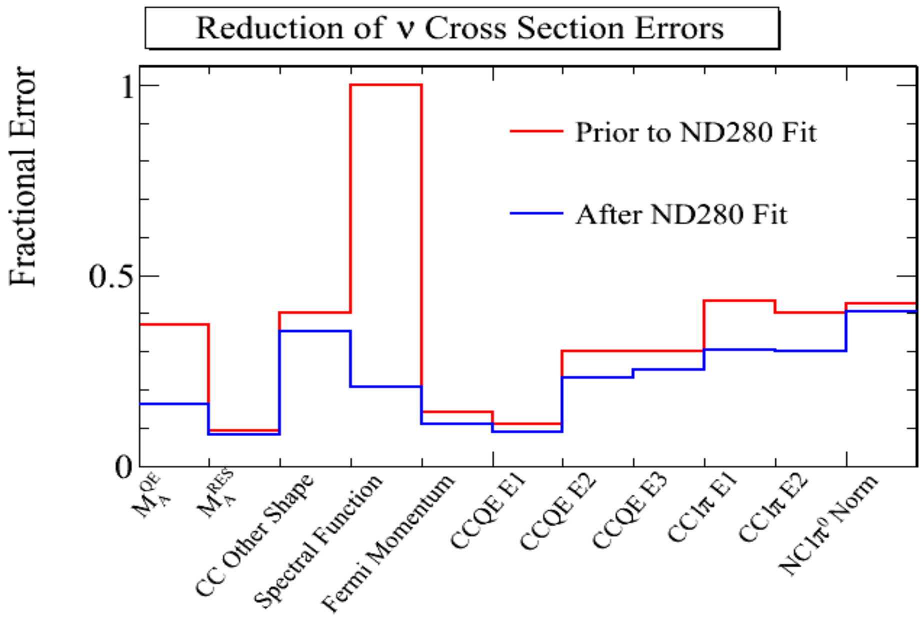
Cross section parameters

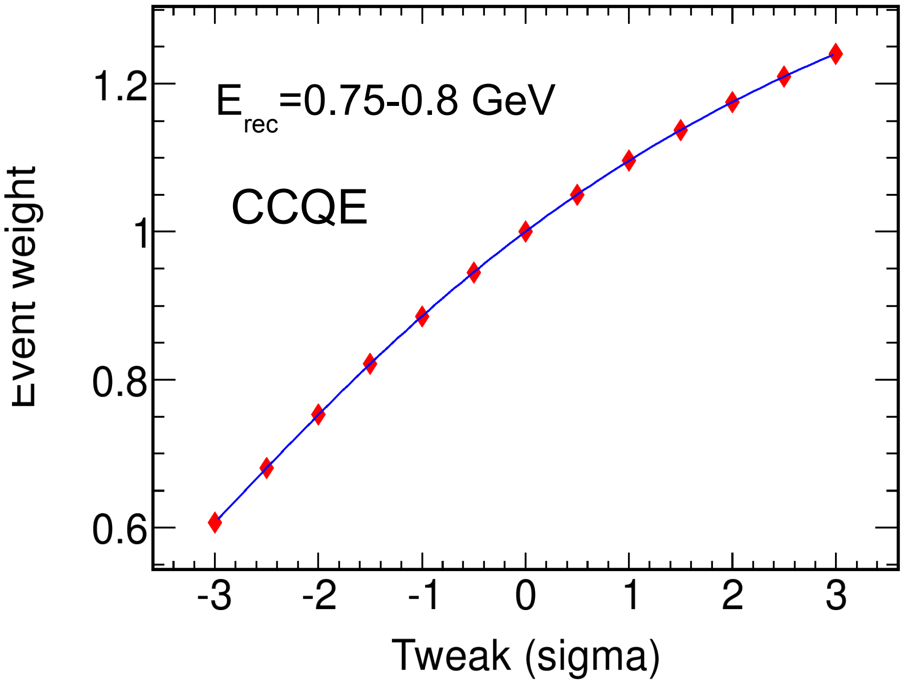
model parameters	Before FIT	After FIT (w/ ND280 measurement)
CCQE M_A [GeV]	1.21±0.45	**1.19±0.19**
CC1π(resonance) M_A [GeV]	1.16±0.11	**1.14±0.10**
Fermi momentum surface P_F [MeV]	217±30	224.6±23.5
Spectral Function	0[off] - 1[on]	0.04±0.21
CC-other cross section shape	0.0±0.4	-0.05±0.35
CCQE E-dependence	1.0±0.11, 1.0±0.11, 1.0±0.11	**0.94±0.09**, 0.92±0.23, 1.18±0.25
CC1π(resonance) E-dep.	1.63±0.43, 1.0±0.4	**1.67±0.28**, 1.10±0.30
NC-π^0 cross sections	1.19±0.43	**1.22±0.40**
CC-coherent π cross section	1−1	same (no additional ND280 constrained)
NC-coherent π cross section	1.0±0.3	same (no additional ND280 constrained)
NC other cross section	1.0±0.3	same (no additional ND280 constrained)
W shape in resonance model [MeV]	87.7±45.3	same (no additional ND280 constrained)
π-less Δ decay	0.0±0.2	same (no additional ND280 constrained)
CC-1π,rNC-1π^0 energy shape	0.0±0.5	same (no additional ND280 constrained)
$\sigma_{\nu e}$ / $\sigma_{\nu\mu}$	1.0±0.03	same (no additional ND280 constrained)

Parameters correlated b/w ND280 and SK

	Prior Value and Uncertainty	Fitted Value and Uncertainty
M_A^{QE} (GeV)	1.21 ± 0.45	1.27 ± 0.19
M_A^{RES} (GeV)	1.41 ± 0.22	1.25 ± 0.13
CCQE Norm. 0-1.5 GeV	1.000 ± 0.110	0.951 ± 0.086
CC1π Norm. 0-2.5 GeV	1.15 ± 0.32	1.37 ± 0.20
NC1π^0 Norm.	0.96 ± 0.33	1.15 ± 0.27

Prior value and uncertainty from fit to MiniBooNE single pion samples





Cross section response function (MAQE)

Systematic error contribution to the predicted number of events in the oscillation analysis

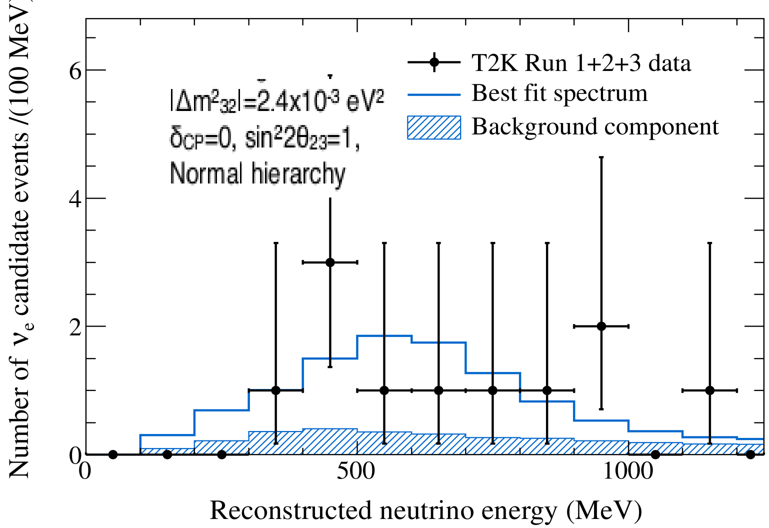
improvement w/ ND measurement

%

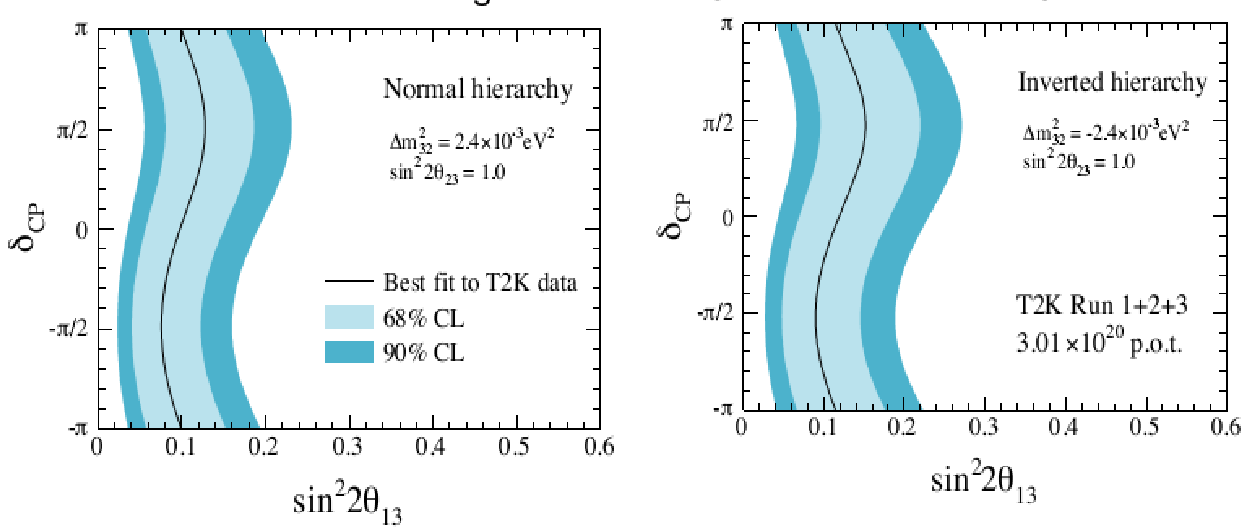
Error source	$\sin^2 2\theta_{13} = 0$ w/o ND measurement	$\sin^2 2\theta_{13} = 0$ w/ ND measurement	$\sin^2 2\theta_{13} = 0.1$ w/o ND measurement	$\sin^2 2\theta_{13} = 0.1$ w/ ND measurement
Beam only	10.8	7.9	11.8	8.5
M_A^{QE}	10.6	4.5	18.7	7.9
M_A^{RES}	4.7	4.3	2.3	2.0
CCQE norm. ($E_\nu < 1.5$ GeV)	4.6	3.7	7.8	6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	5.3	3.7	5.5	3.9
NC1π^0 norm.	8.1	7.7	2.4	2.3
CC other shape	0.2	0.2	0.1	0.1
Spectral Function	3.1	3.1	5.4	5.4
p_F	0.3	0.3	0.1	0.1
CC coh. norm.	0.2	0.2	0.2	0.2
NC coh. norm.	2.1	2.1	0.6	0.6
NC other norm.	2.6	2.6	0.8	0.8
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	1.8	1.8	2.6	2.6
W shape	2.0	2.0	0.9	0.9
pion-less Δ decay	0.5	0.5	3.5	3.5
CC1π, NC1π^0 energy shape	2.5	2.5	2.2	2.2
SK detector eff.	7.1	7.1	3.1	3.1
FSI	3.1	3.1	2.4	2.4
SK momentum scale	0.0	0.0	0.0	0.0
Total	21.5	13.4	25.9	10.3

Method 2 and 3

- Fit to rate + E_{ν}^{rec} :

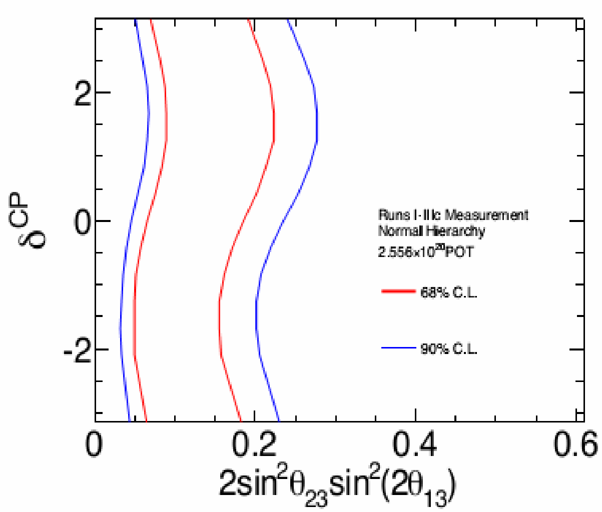


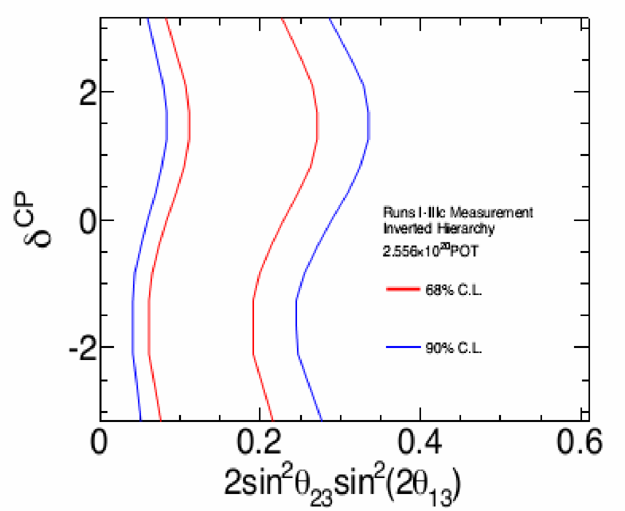
Allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}



w/ 2.56 x 10^{20} p.o.t.

- Rate only:

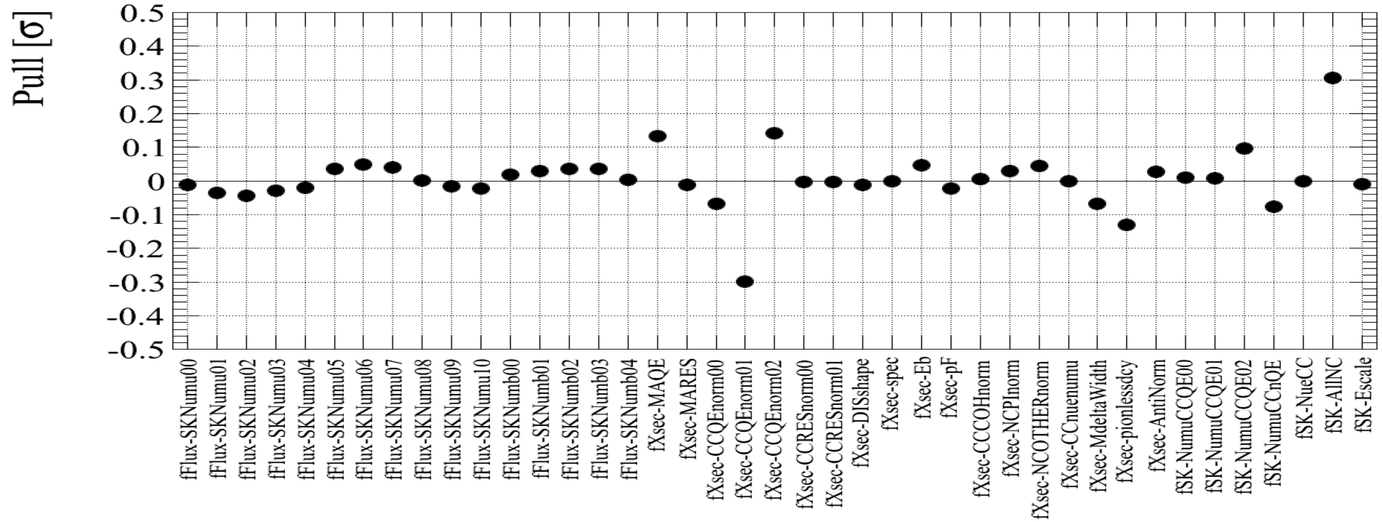




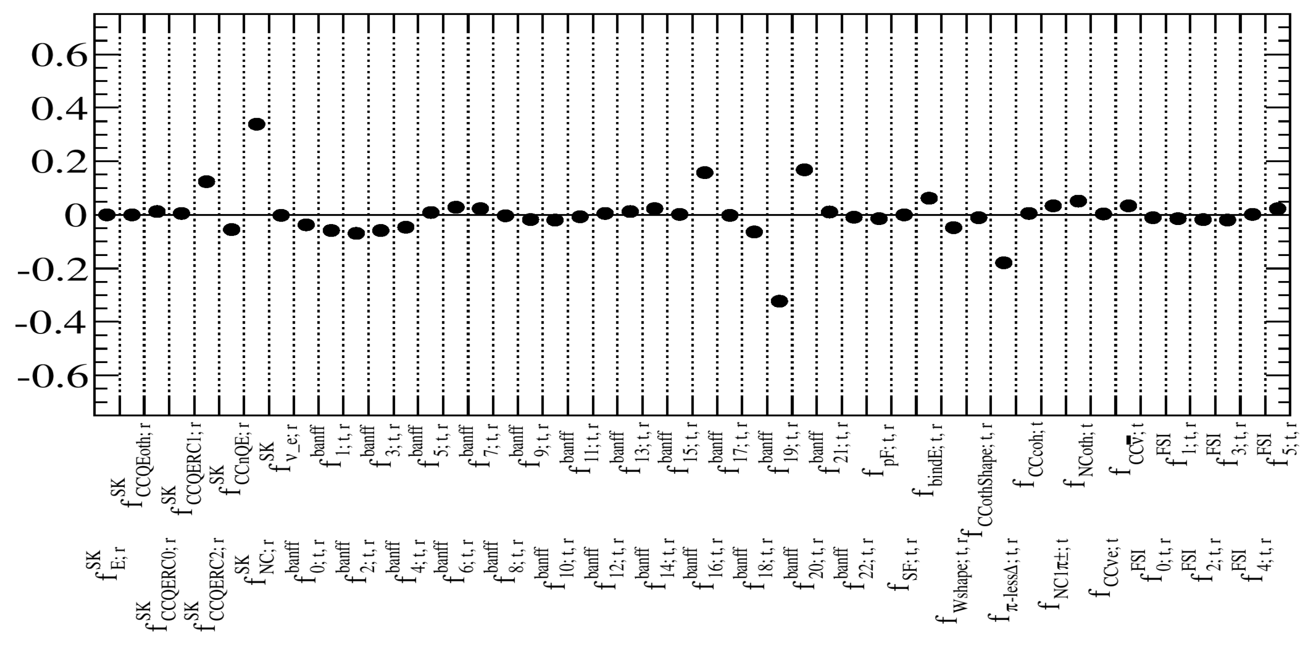
All three analysis methods give consistent results!

Systematic parameter pull (ν_μ fit)

Extended maximum likelihood



Binned likelihood ratio



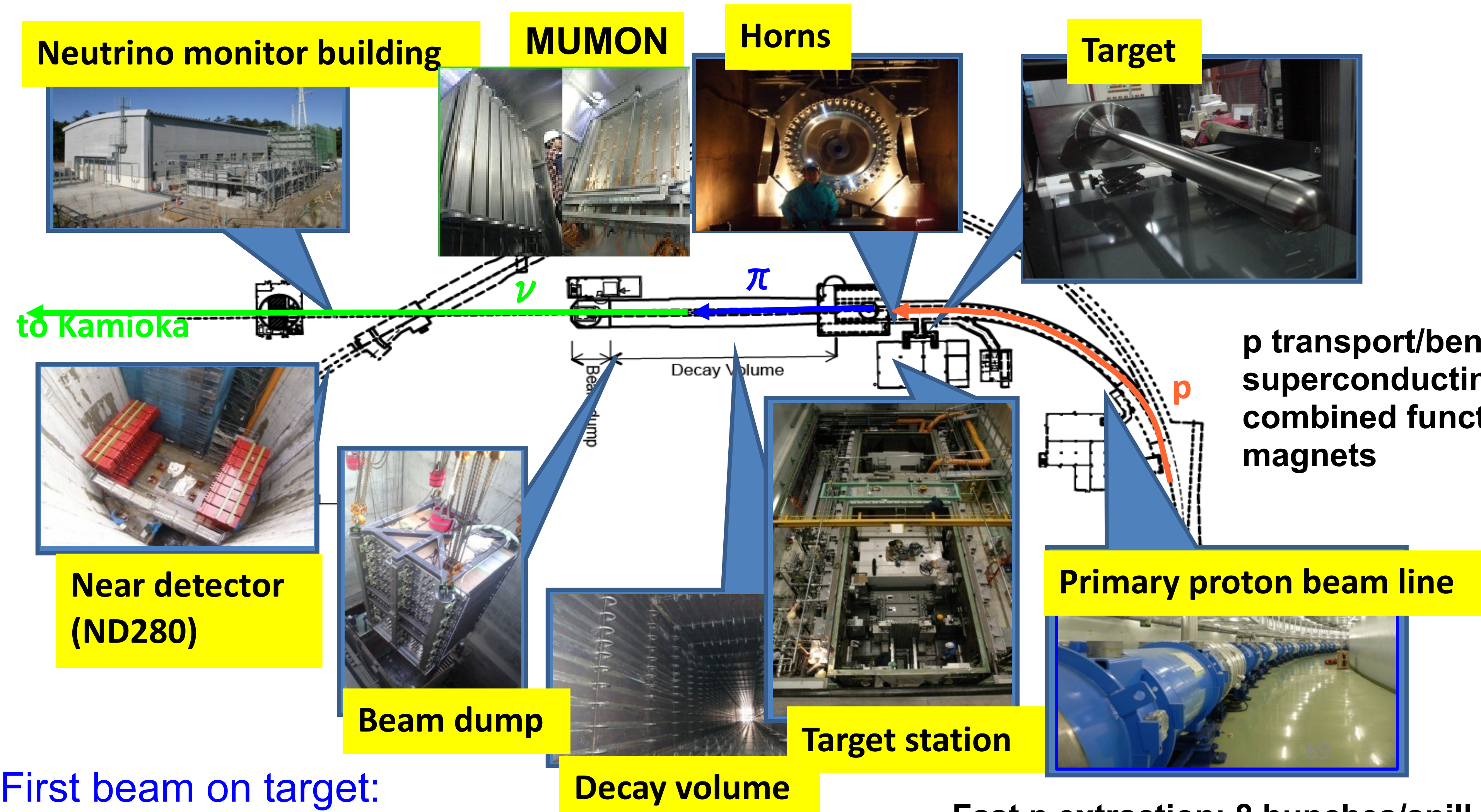
Neutrino beam line

Conventional beam:
p+C → π → ν+μ

Muon monitors:
Ionization chambers
+ SiPIN diode

3 focusing horns
(250 kA)

Target:
graphite (ø26mm x 90cm)
He gas cooled



p transport/bending:
superconducting
combined function
magnets

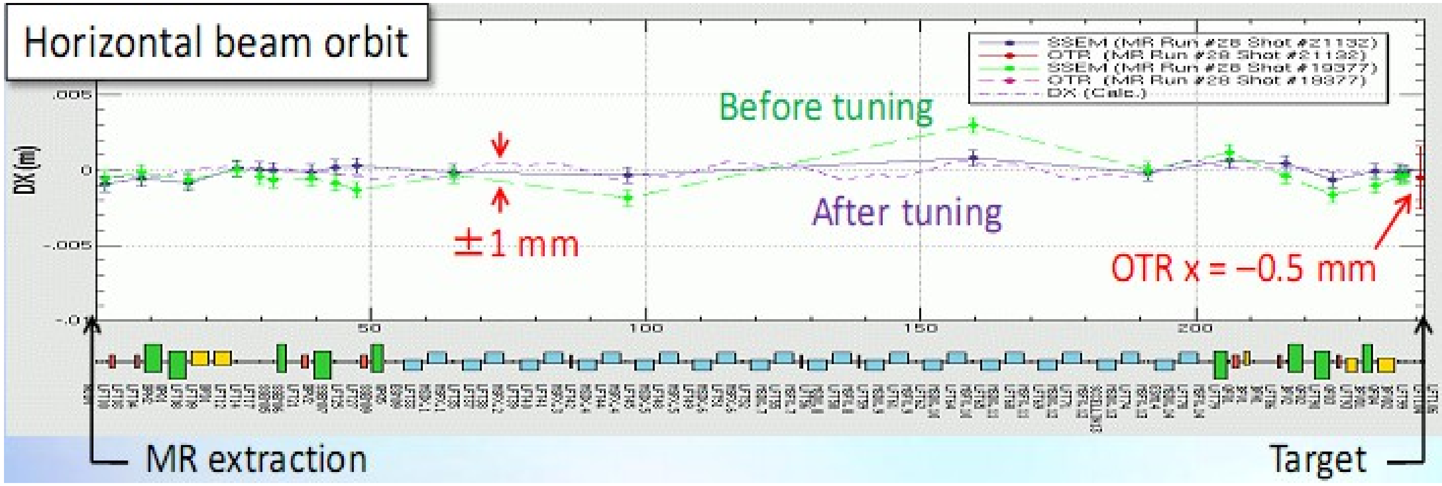
First beam on target:
April 23, 2009

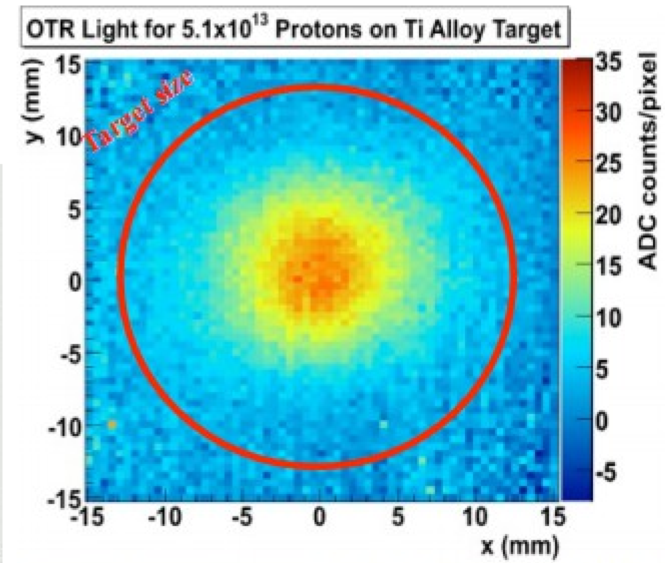
Decay volume (96 m)
He filled

Fast p extraction: 8 bunches/spill,
581 ns separation, 2.5-3.0 s spill period

Beam monitors

Proton beam precisely tuned (<2mm) to minimize beam loss, and control direction of secondary beam

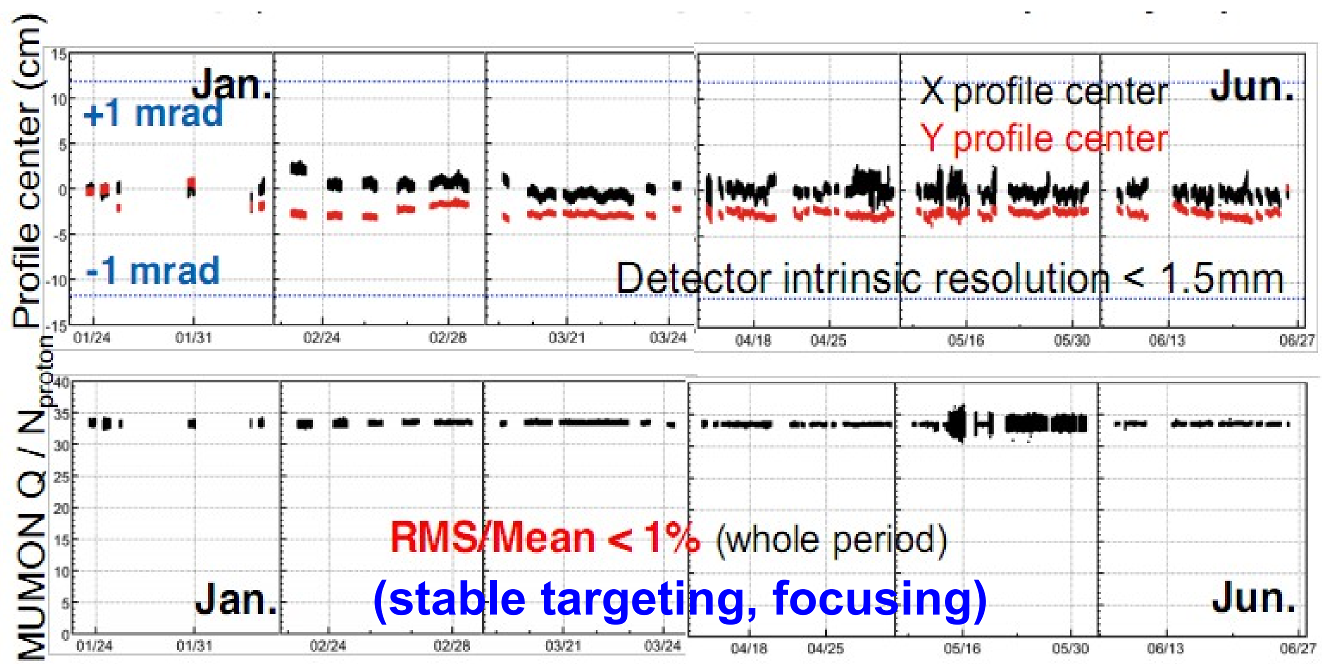




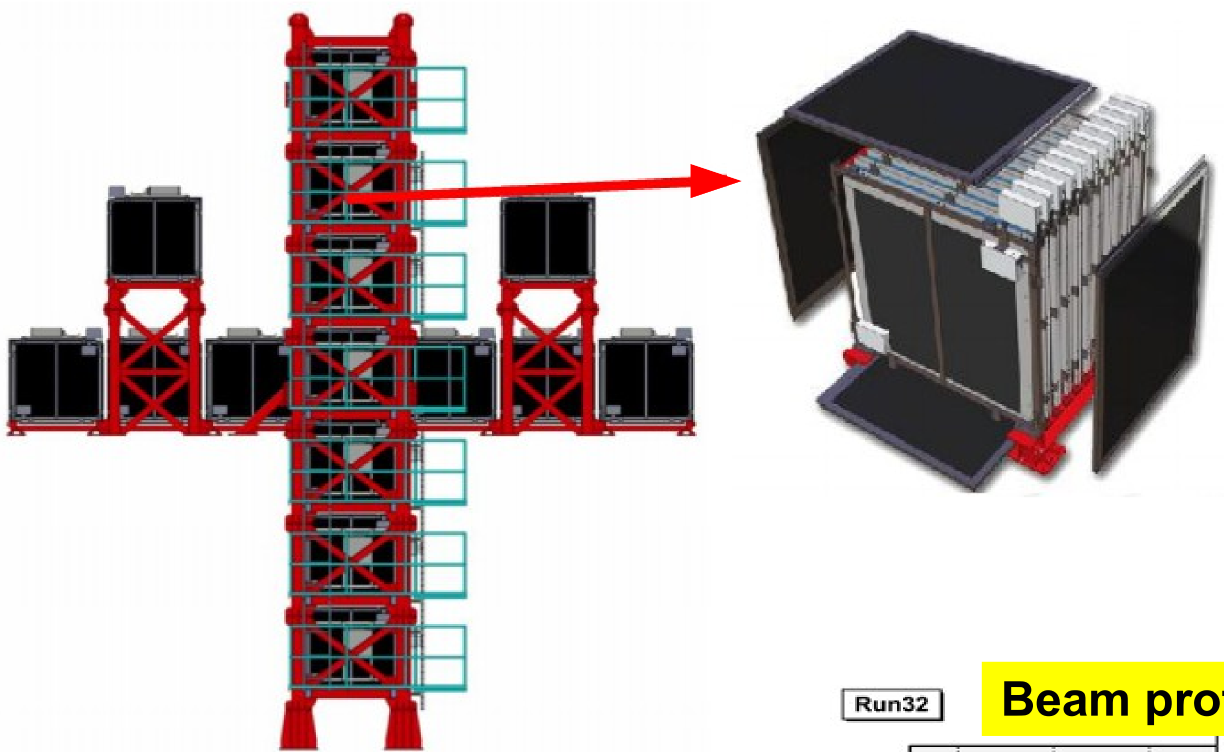
Optical transition radiation detector (OTR) immediately upstream of target:

Muon monitors (Si PIN and ionization chambers):

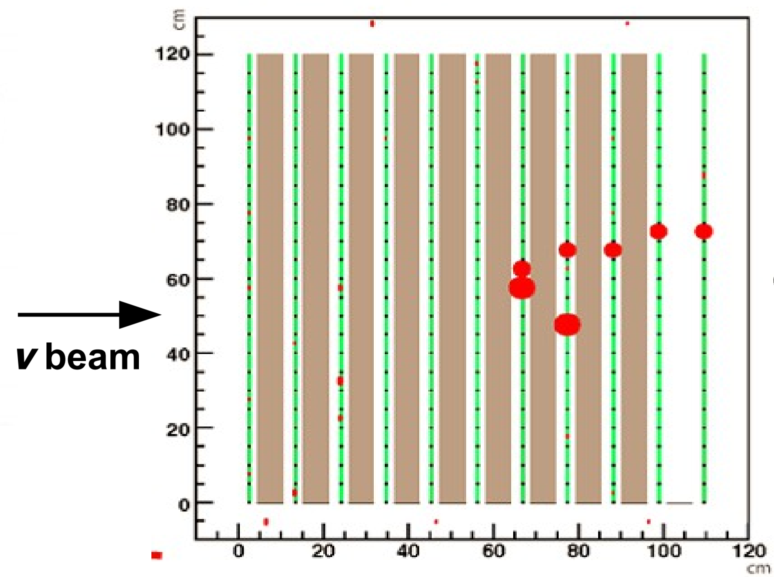
- Measure secondary beam direction and intensity spill-by-spill
- Direction is well within 1mrad ($\Delta\Phi$ ~ 2%/mrad at the peak energy)



INGRID: on-axis near detector



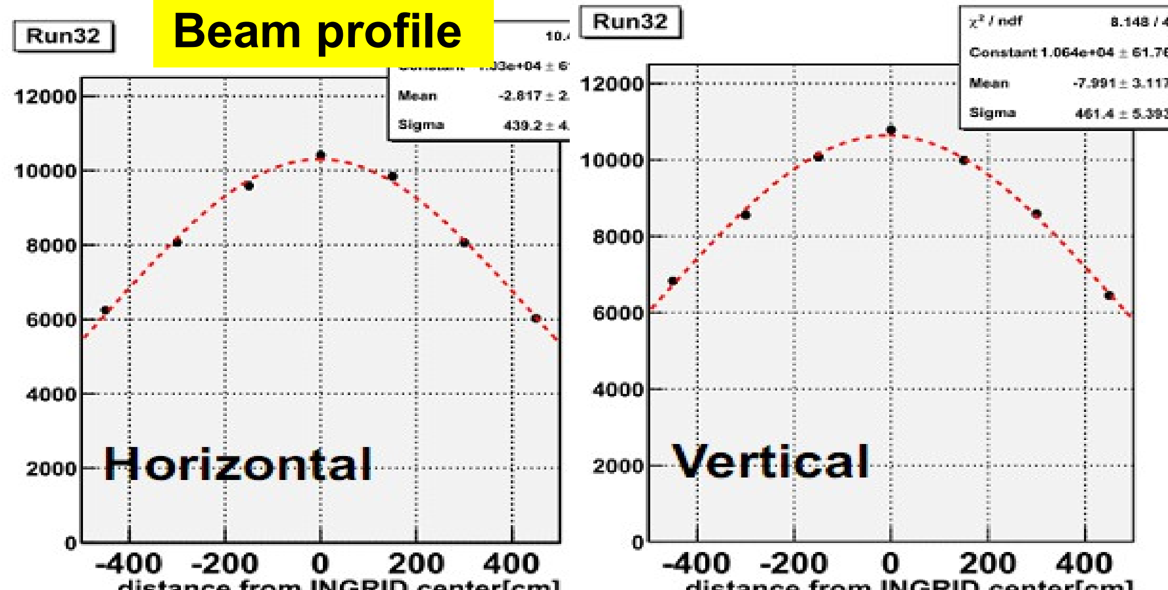
Typical CC event in one module



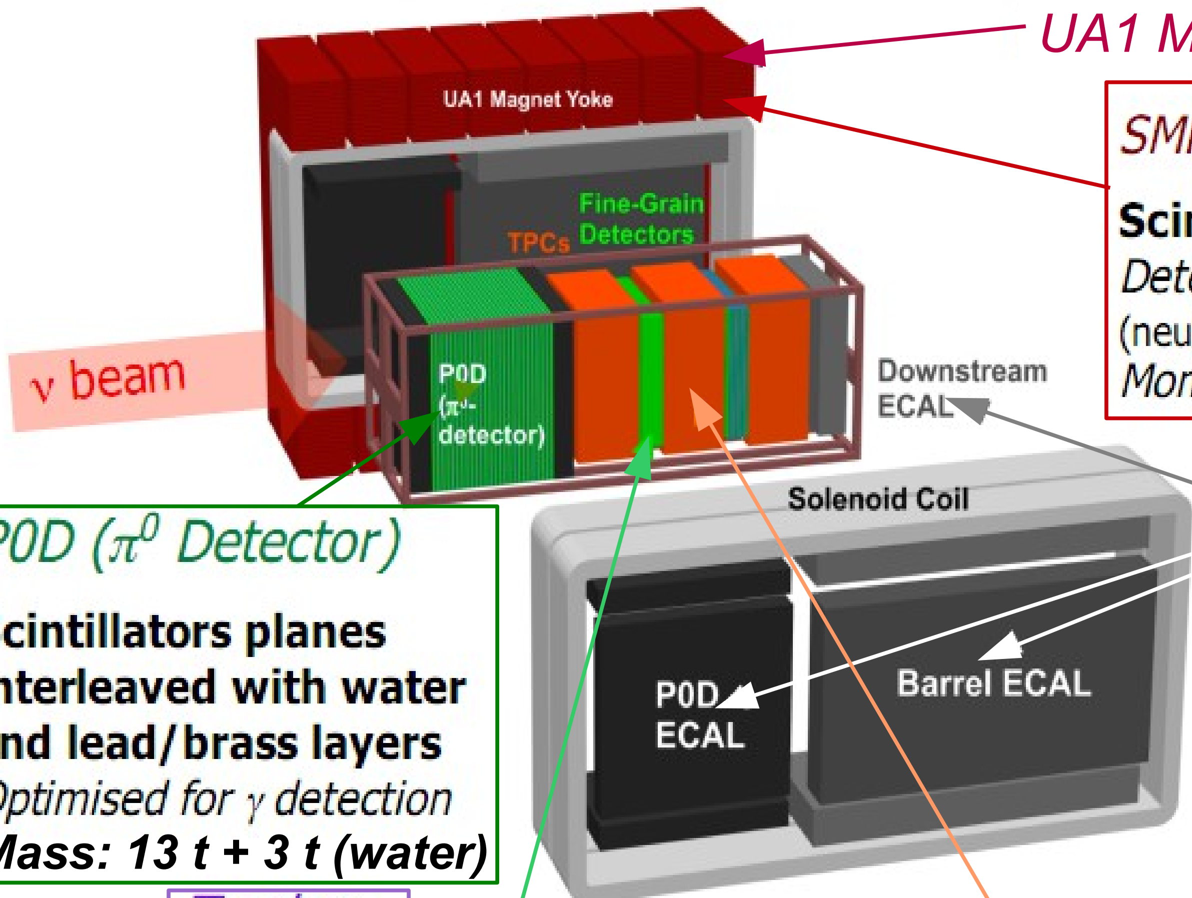
7+7 horizontal/vertical + 2 off-cross + 1 proton (no iron) modules

- alternating scintillator/iron planes + veto planes (7 tons/module)
- coverage 10x10 m^2
- 700 interactions/day (@ 50kW)

Beam profile



ND280: off-axis near detector



UA1 Magnet: 0.2 T

SMRD (Side Muon Range Detector)
Scintillator planes in magnet yoke.
Detect muons from inner detector
(neutrino rate, side muon veto, cosmic trigger)
Momentum measurement

P0D (π^0 Detector)
Scintillators planes interleaved with water and lead/brass layers
Optimised for γ detection
Mass: 13 t + 3 t (water)

P0D, Barrel and DownStream ECAL
Scintillator planes with radiator
Measure EM showers from inner detector
(γ for NC π^0, bremstrahlung in ν_e measurement)
Sand muon rejection

Tracker

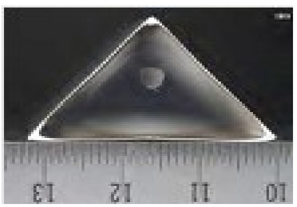
2 FGDs (Fine Grained Detectors)
Thin, wide scintillator planes
Provides active target mass
Optimised for p recoil detection

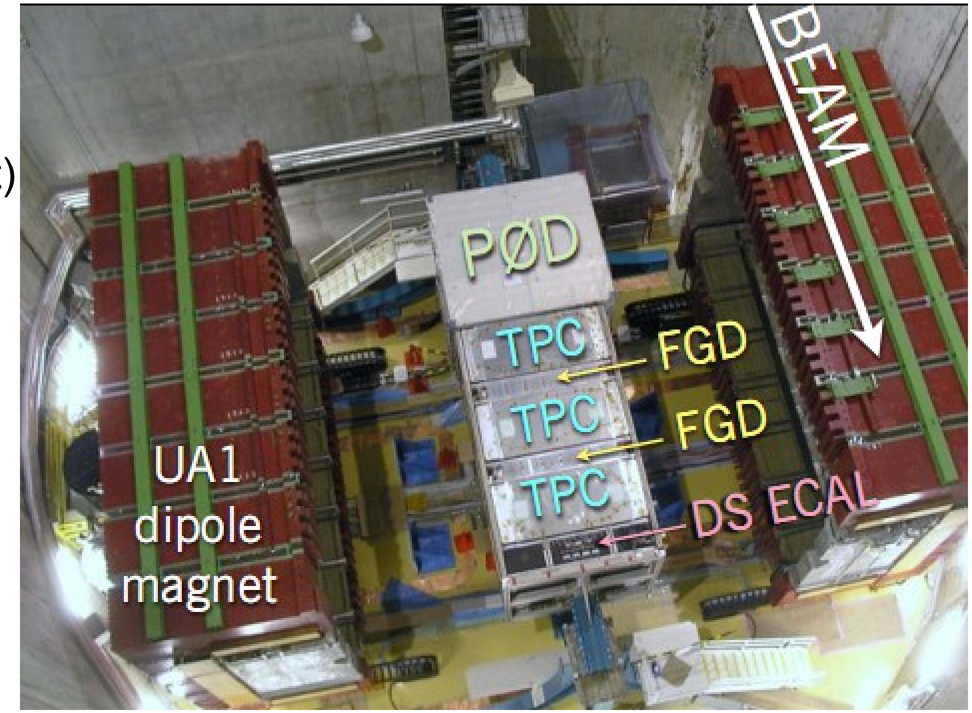
3 TPCs (Time Projection Chambers):
Momentum measurement of charged particles from FGD and P0D
PID via dE/dx measurement

FGD1: 1t & FGD2: 0.5 t (scint) + 0.5 t (water)

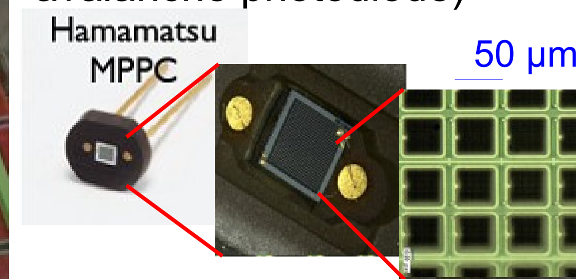
ND280: off-axis near detector

Pi0 detector (P0D): target
40 x-y scintillator planes
(~10k scint. bars)
Middle: scint+H_2O bags (11t)
Front/back: calorimeter
(veto and γ catcher)
Pb+Scint (6.4t)

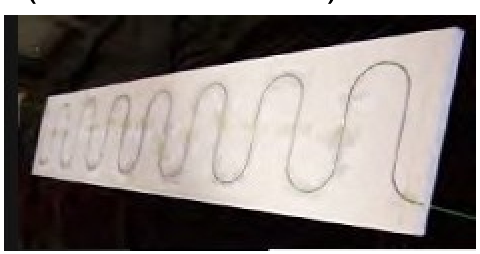




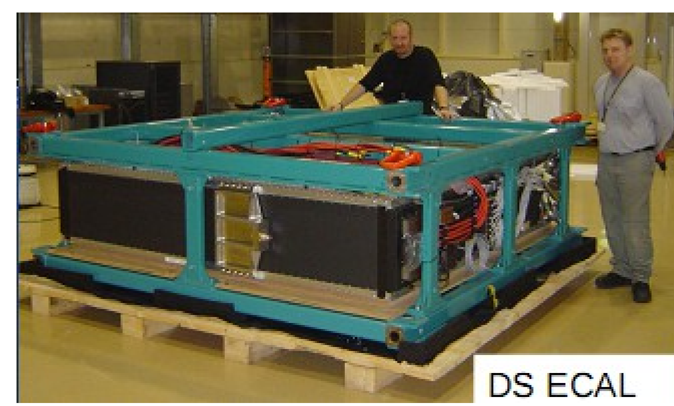
Scintillator detectors read out via WLS fiber coupled to Si MPPC (667 pixel avalanche photodiode)



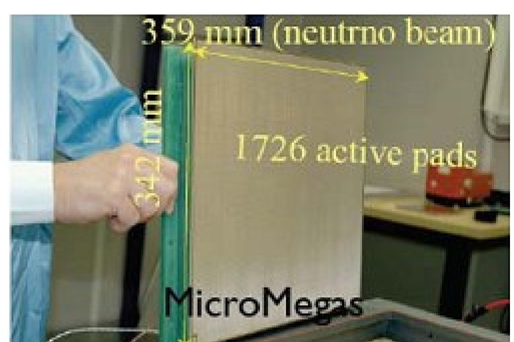
SMRD: μ range, veto
cosmic trigger
~2k scint. counters
(87x17x0.7 cm3)



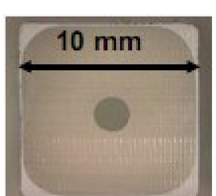
ECal: x-y fine grained
Pb+Scint. (4x1 cm^2)
~21k scint. bars (total)
$\sigma E/E \sim 7.5\%/\sqrt{E}$



Time Projection Chambers (TPC):
wireless readout with MicroMegas
(7x10mm^2 pads) ~124k channels
5σ e/μ separation, $\sigma_p/p < 10\%$



Fine Grained Detectors (FGD):
x-y scintillator planes
(~8.4k scint. bars)
+ H_2O (in FGD2)



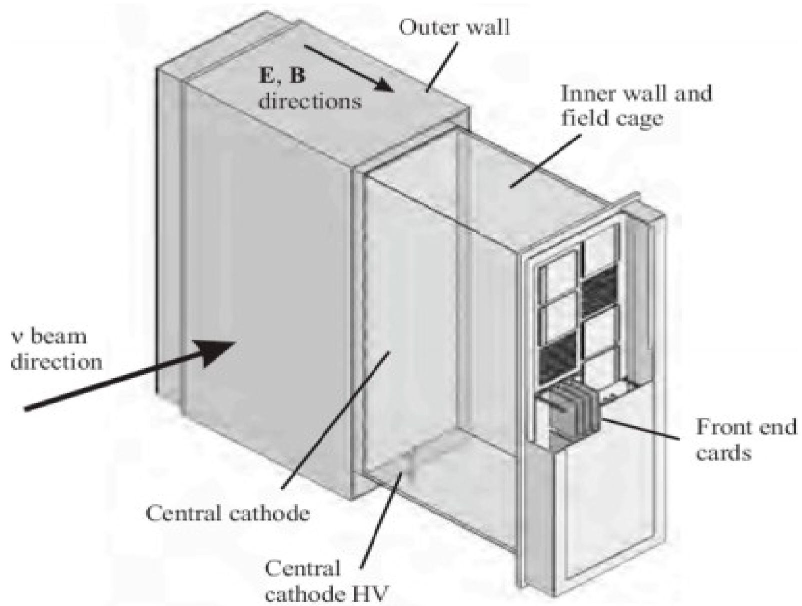
Time Projection Chambers

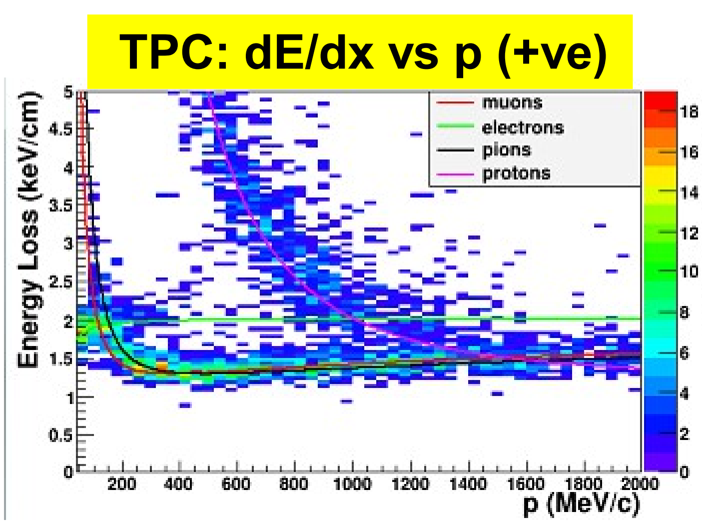
Novel technology: "wireless" TPC

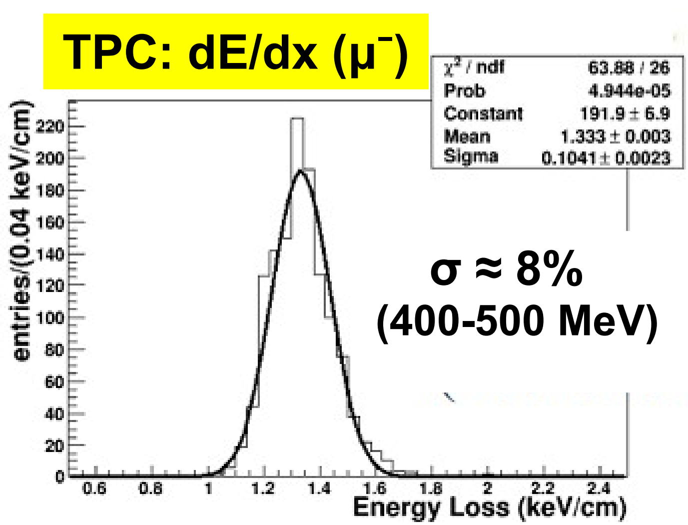
- Strong electric field at MicroMegas mesh creates a shower of electrons detected by 6.9x9.7 mm2 pads (12 MM with 1728 pads each)

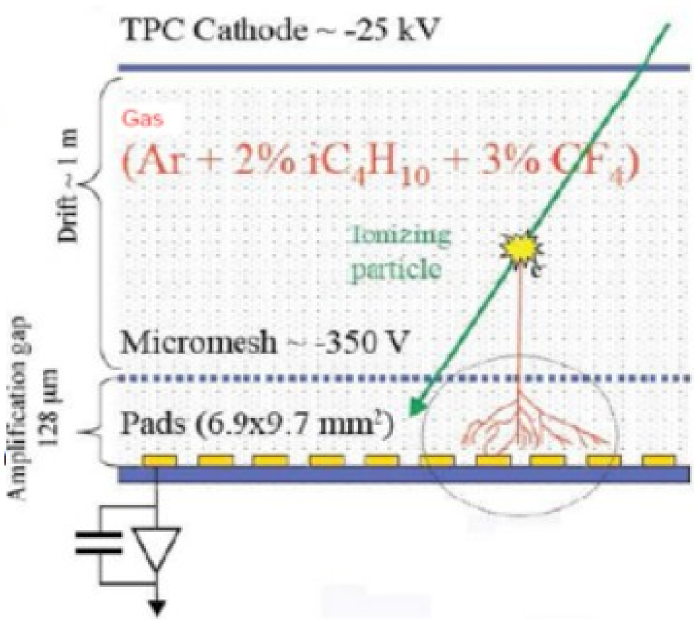
Resolution:

- spatial: 600 μm @ 1m drift distance
- momentum: <10% @ 1 GeV (B=0.2 T)
- PID: σ(dE/dx) ~8% at 0.6 GeV

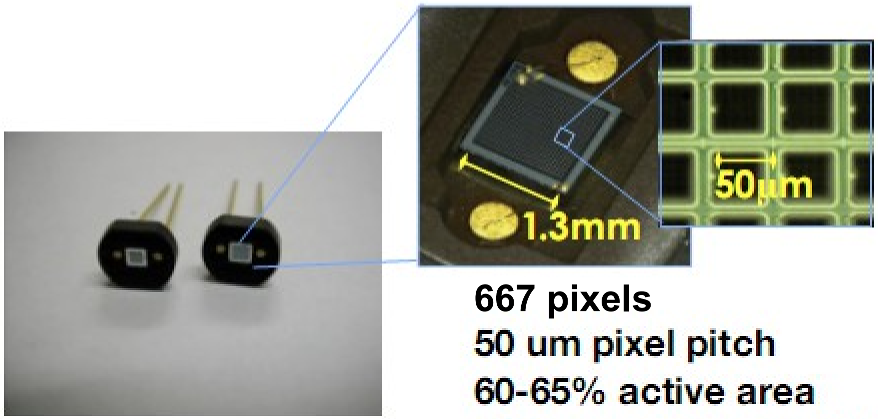




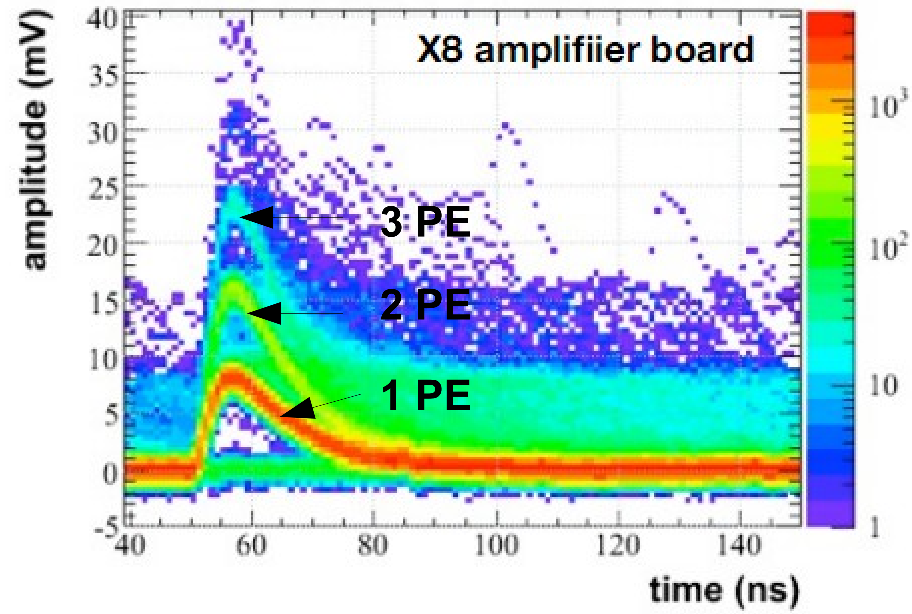




Multi-Pixel Photon Counters (MPPC)

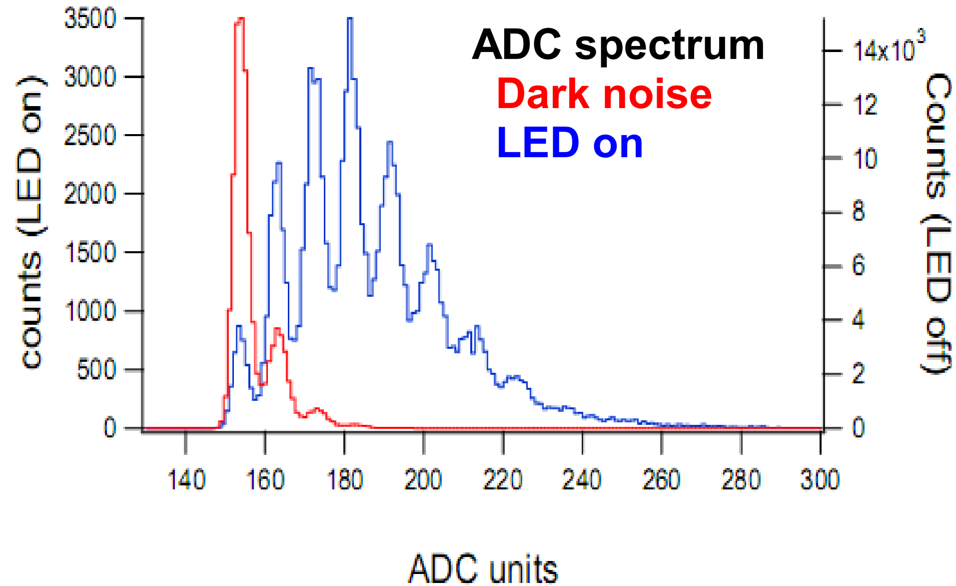


667 pixels
50 um pixel pitch
60-65% active area
Pixel capacitance : 97.5 fF
Passive quenching 150 MΩ
Pixel RC cnst~13 ns

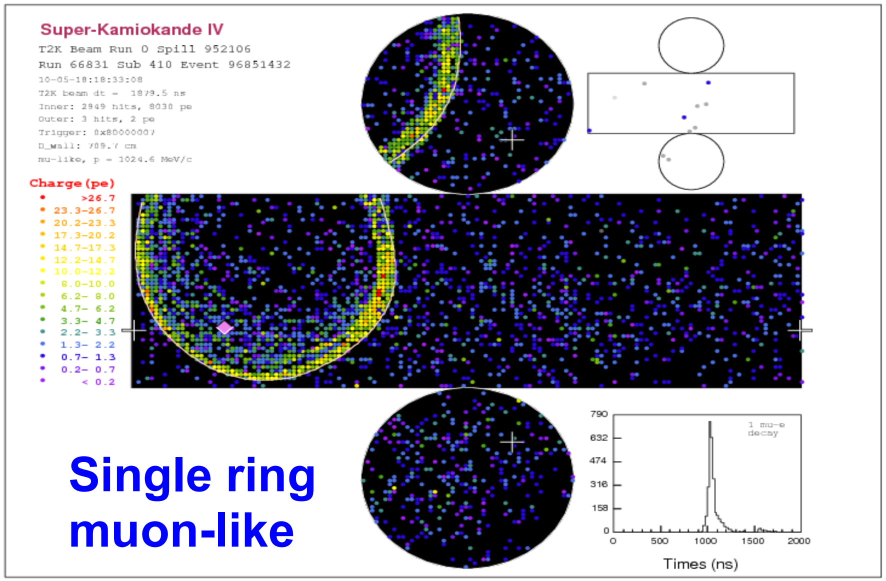


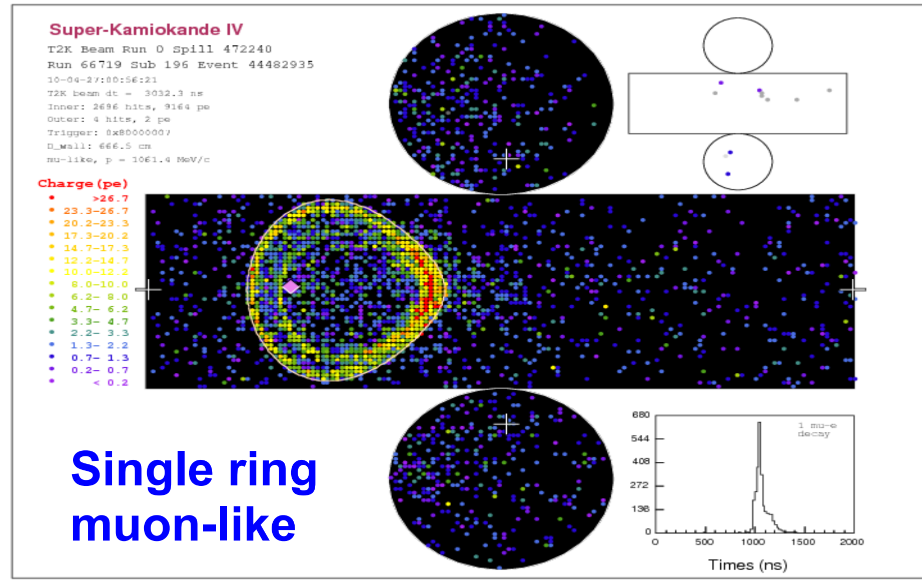
T2K is the first experiment to use MPPCs at a large scale (~56000 pieces)

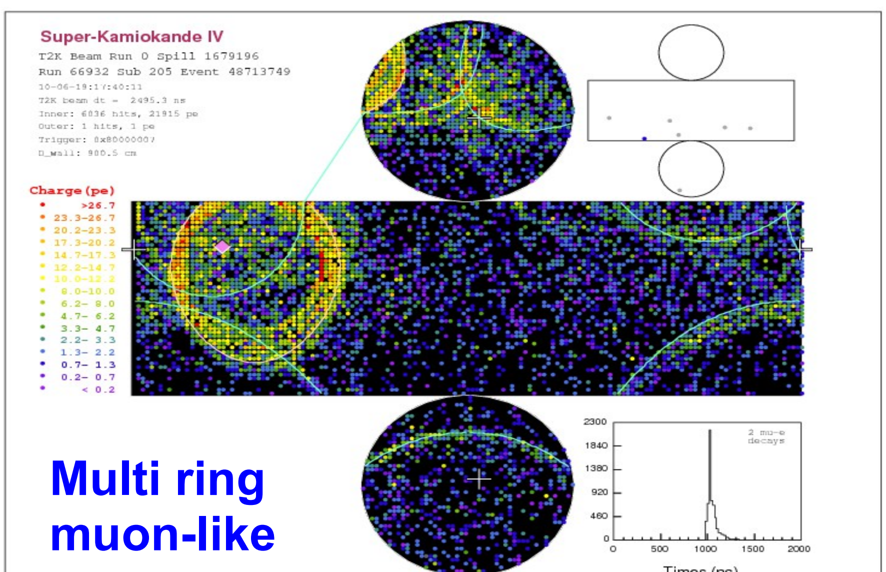
- operated in limited Geiger mode (~1V above breakdown voltage)
- nominal gain: 7.5×10^5
- PDE (500 nm): ~20%
- insensitive to magnetic field
- thermal noise: 500 MHz (20C)
- cross talk and after pulsing: ~15%

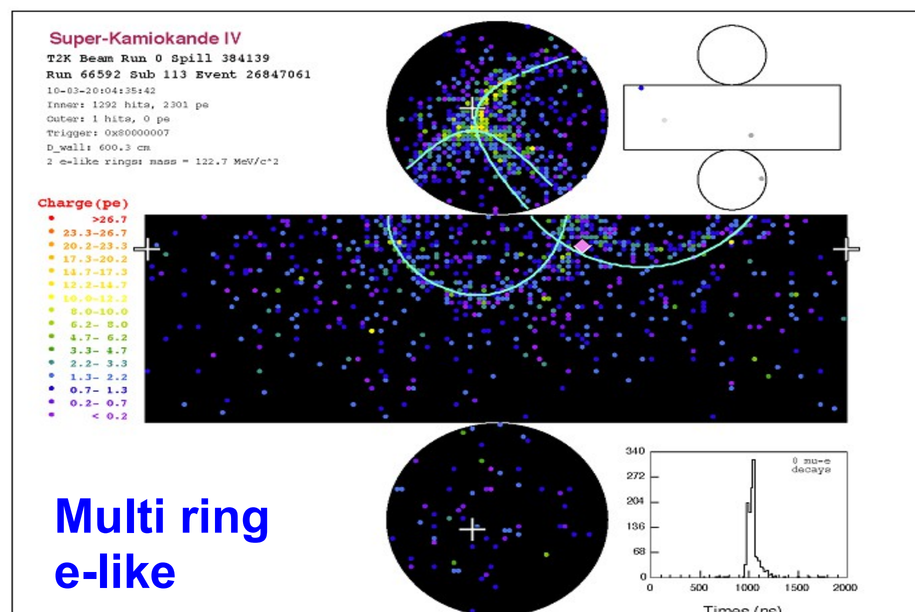


SK event gallery

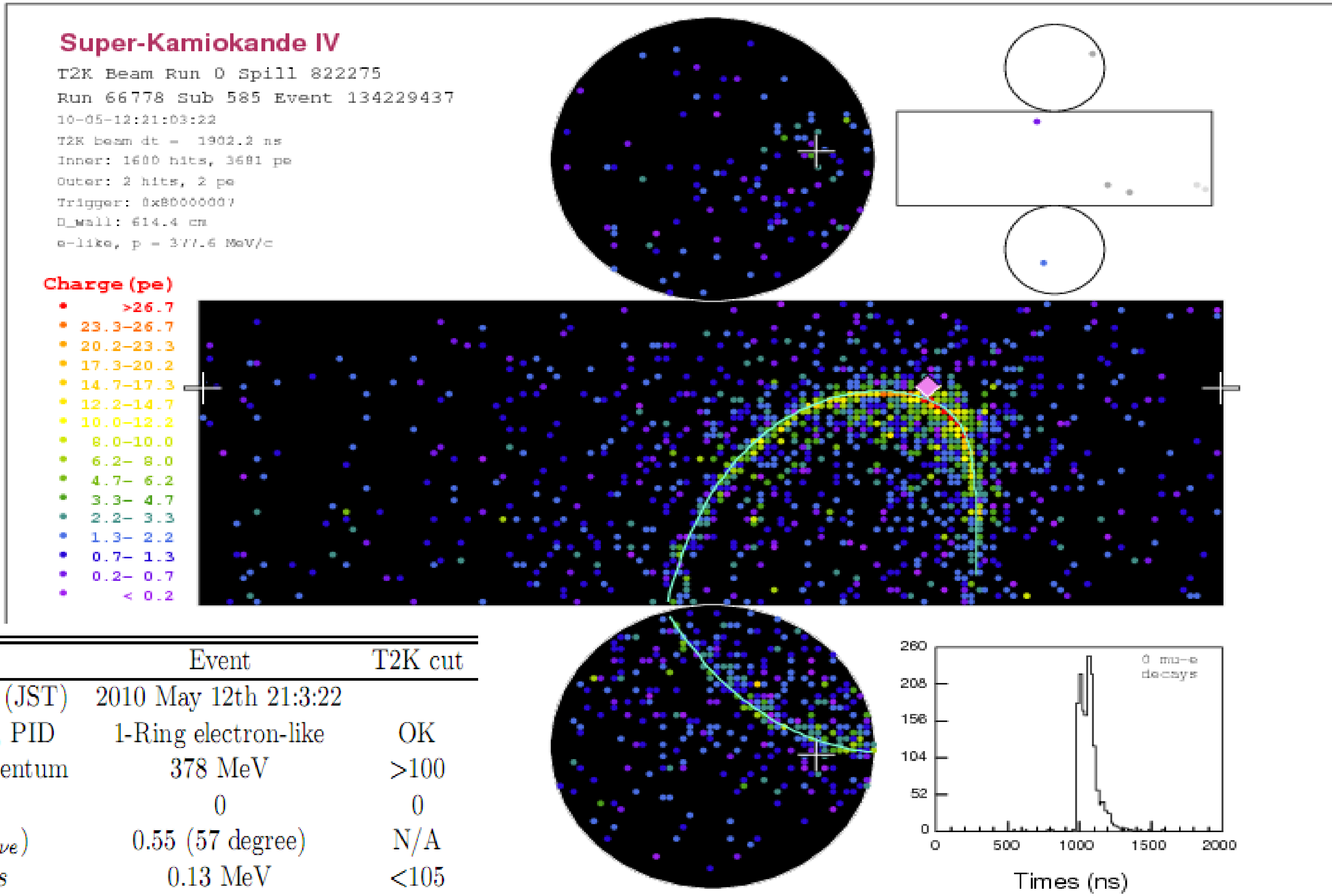








First ν_e event candidate



Item	Event	T2K cut
Date (JST)	2010 May 12th 21:3:22	
Ring, PID	1-Ring electron-like	OK
Momentum	378 MeV	>100
N_{dcy}	0	0
$\cos(\theta_{\nu e})$	0.55 (57 degree)	N/A
$Mass$	0.13 MeV	<105
E_{rec}	496 MeV	<1250

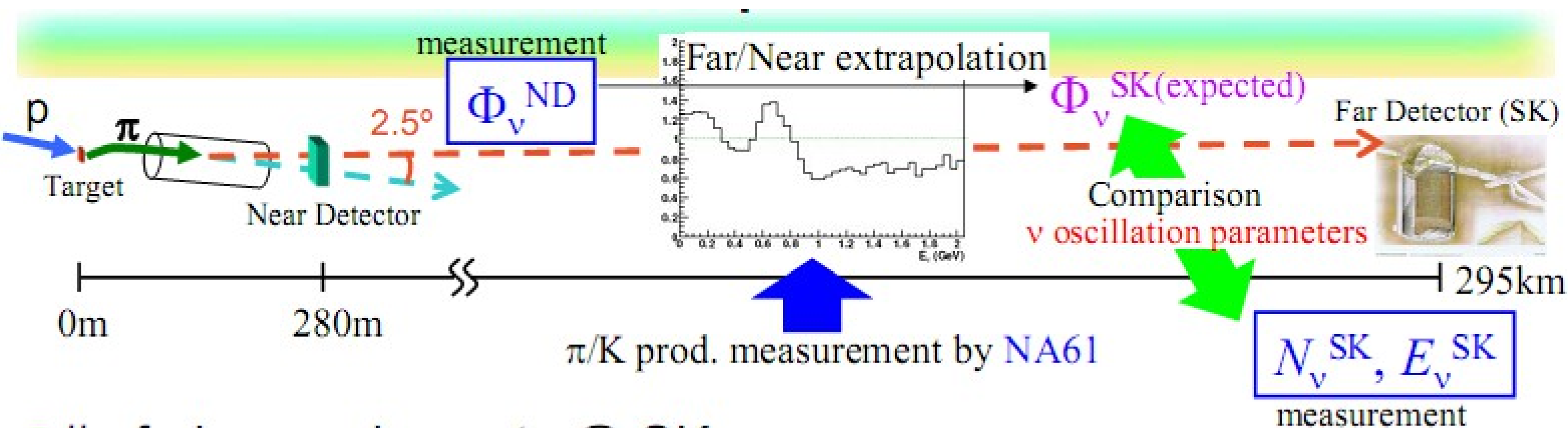
T2K collaboration

~500 members, 56 institutions, 11 countries

Canada, France, Germany, Italy, Japan, Poland, Russia, Spain, Switzerland, UK,

US:
Boston U.
Colorado S.U.
Duke U.
Louisiana S.U.
Stony Brook U.
UC Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

Analysis concept



- \# of observed events @ SK:

  $N\nu e^{SK} = P(\nu_\mu \rightarrow \nu_e) \times \boxed{\Phi^{SK}(\nu_\mu) \times \sigma(\nu \text{ interaction})}$

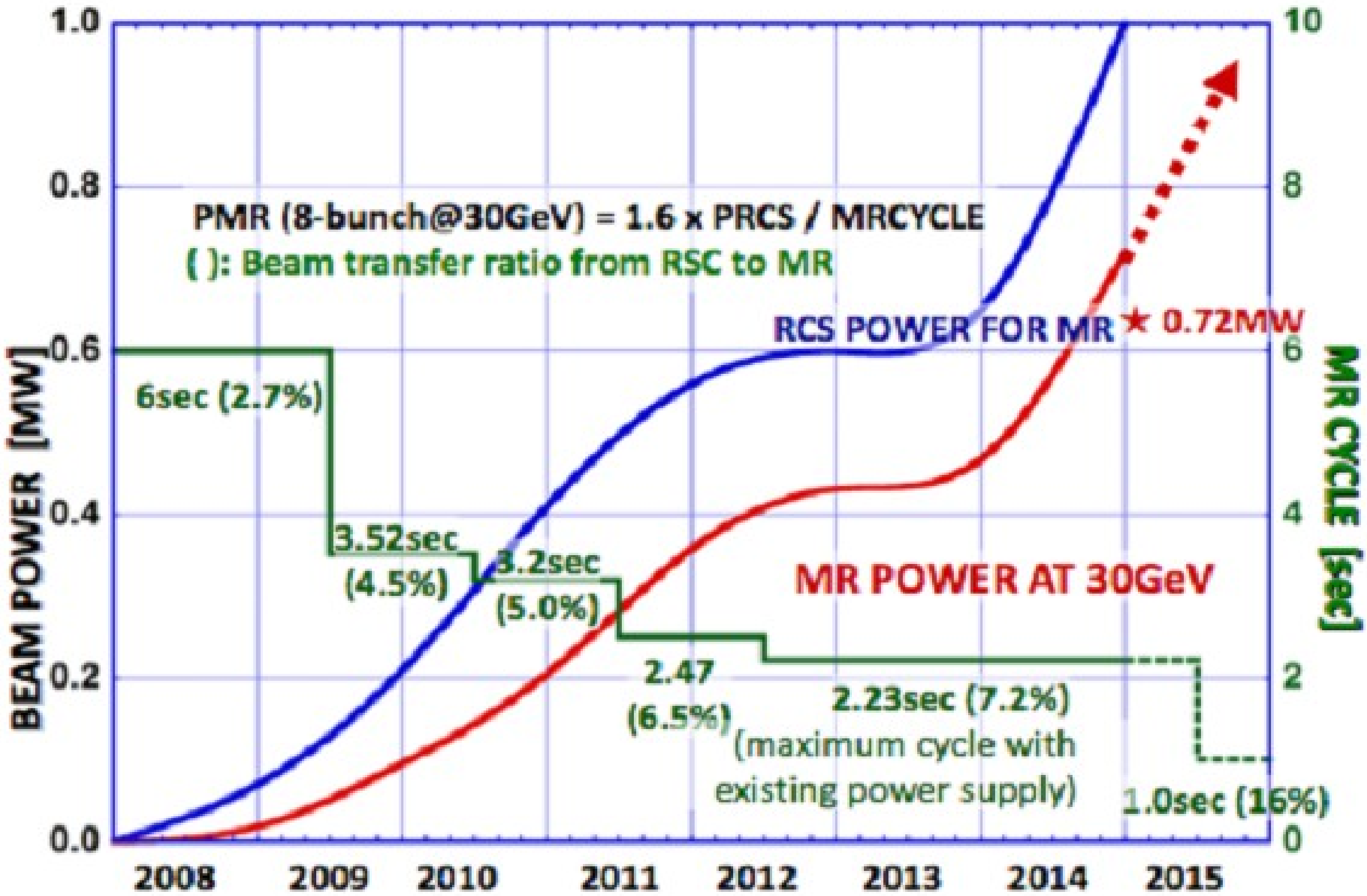
- $\boxed{\Phi^{SK}(\nu_\mu) \times \sigma(\nu \text{ int.})} = R(SK/ND) \times \Phi^{ND}(\nu_\mu) \times \sigma(\nu \text{ int.})$

  $= R(SK/ND) \times N\nu_\mu^{ND} \leftarrow$ ND measurement.

- $R(SK/ND)$: Far to Near flux extrapolation.
  - Targeting condition: Measured by proton beam monitors.
  - p_π, θ_π distribution : Measured by CERN NA61

"Beam MC"

Accelerator power



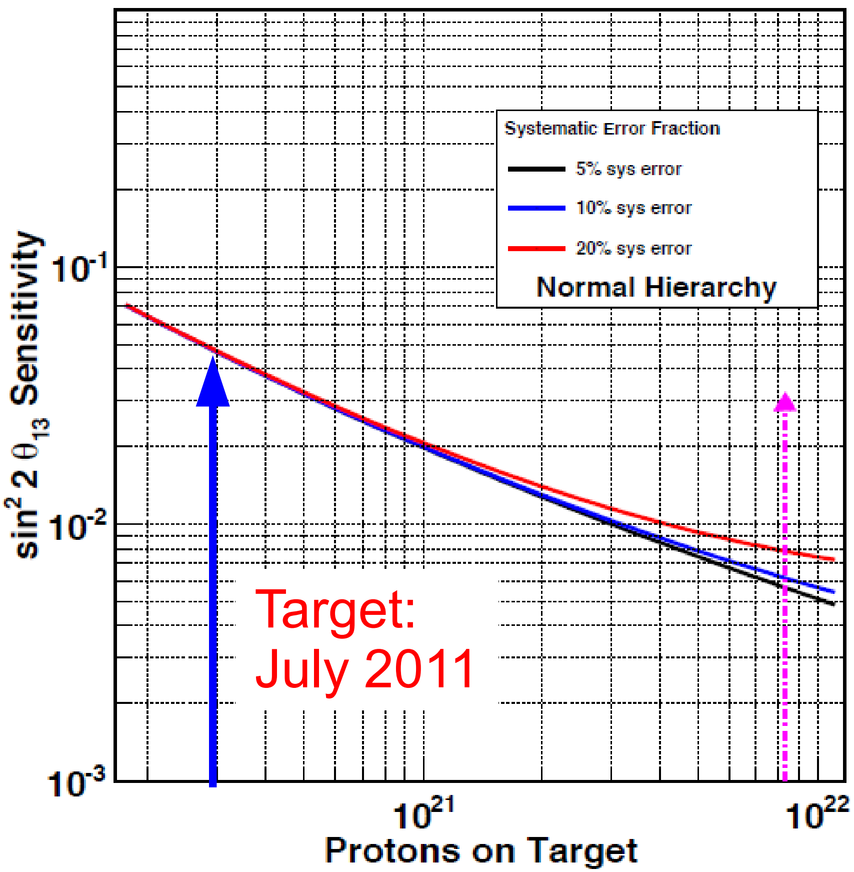
Ultimate sensitivity

- ν_e appearance:

$\sin^2 2\theta_{13} < 0.008$ (90% C.L.)

5 x 0.75 MW x 10^7s (8.3 x 10^{21} PoT)

90% CL θ_{13} Sensitivity

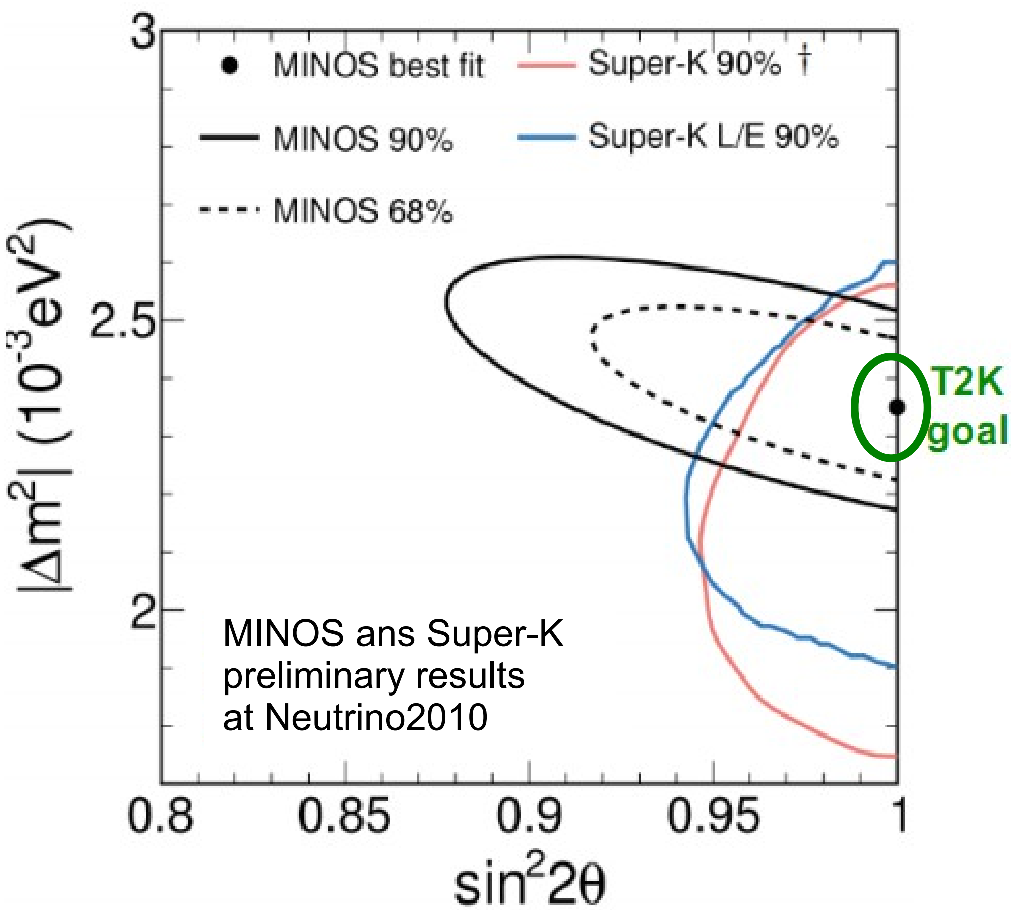


($\Delta m^2_{23}=2.4\times10^{-3}$ eV^2, δ_{CP}= 0)

- ν_μ disappearance:

$\delta(\sin^2 2\theta_{23})\approx 0.01$ & $\delta(\Delta m^2_{23})<1\times10^{-4}$ eV^2 (90% C.L.)

5 x 0.75 MW x 10^7s (8.3 x 10^{21} PoT)

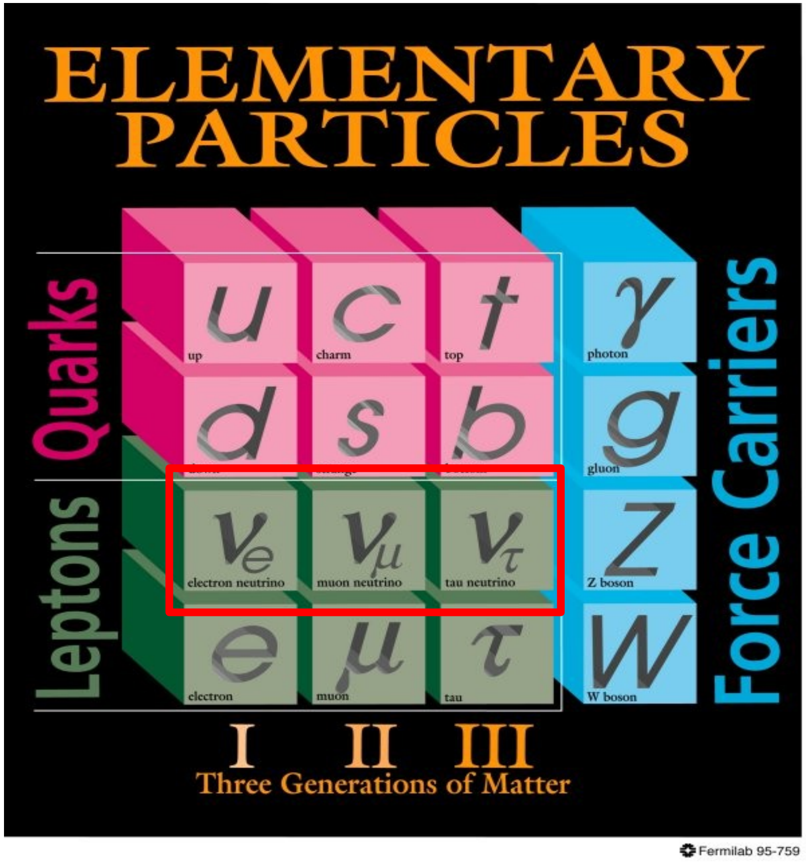


Neutrinos in the Standard Model

Properties of neutrinos (neutral leptons):

- Three light (active) neutrinos
- No electric charge or color → only weak interaction
- left-handed neutrino (right handed anti-neutrino)
- massless (no right-handed neutrinos):

$$m\,(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$$



Neutrino oscillation can only happen if neutrinos have mass - first direct evidence for new physics beyond the SM

How the neutrino mass is generated is still a mystery (Dirac or Majorana, see-saw mechanism?)

Fermilab connection

- Horn-2 development/construction – MiniBooNE experience
- Scintillator extrusion R&D – in particular P0D scintillator bars (same as MINERvA's) were produced in Lab 6 (PPD/Tech Center)
- Fiber mirrors for P0D/FGD (PPD/Tech Center)
- Front-end Electronics for P0D/ECal/SMRD: Trip-t ASIC based read out (D0, MINERvA – PPD/EED)